CITY OF BALTIMORE

Sheila Dixon
Mayor

DEPARTMENT OF PUBLIC WORKS

David E. Scott, P.E.
Director of Public Works

BUREAU OF WATER AND WASTEWATER
WATER & WASTEWATER ENGINEERING DIVISION

High Level Sewershed Model Development and Calibration Report
PROJECT 1028

January 2009
Revised August 2009

Kishia L. Powell, P.E., Bureau Head
Bureau of Water & Wastewater

Wazir Qadri, Acting Chief
Water & Wastewater Engineering Division

BALTIMORE HIGH LEVEL SEWERSHED MODEL DEVELOPMENT AND CALIBRATION REPORT

Prepared by:

HydroQual, Inc.
1200 MacArthur Blvd.
Mahwah, NJ 07435
201-529-5151

January 2009
JMAT.001.009.00

BALTIMORE HIGH LEVEL SEWERSHED
MODEL DEVELOPMENT AND CALIBRATION REPORT
PROJECT #1028
TABLE OF CONTENTS

Section — Page

EXECUTIVE SUMMARY **1**

SECTION 1 - INTRODUCTION **1**

1.1 Background **1**

1.2 Modeling Objectives **3**

1.3 REPORT ORGANIZATION **4**

SECTION 2 – HIGH LEVEL SEWERSHED **5**

2.1 Sewershed Description **5**

2.2 Interactions with Other Sewersheds **5**

2.3 Model Extent **9**

SECTION 3 – MODELING TOOL AND MODELING PROCEDURE **10**

3.1 Modeling Tool – InfoWorks CS **10**

3.2 Model Framework **11**
3.2.1 Hydrology Calculation 11
3.2.2 Hydraulic Calculations 13

3.3 Modeling Procedure **14**
3.3.1 General Modeling Procedure 14
3.3.2 BaSES Guidance for Baltimore Projects 17

SECTION 4 – DATA SOURCES AND ANALYSIS TO SUPPORT HYDRAULIC MODEL DEVELOPMENT **19**

4.1 Data Sources **19**
4.1.1 Flow Monitoring 19
4.1.2 Historical SSO Records 25
4.1.3 GIS Data in HLSS 30
4.1.4 Field Data Collection 37
4.1.5 City-wide Macro Model 41
4.1.6 Engineered SSO Locations 42
4.1.7 Reports and Protocols 46

4.2 Rainfall Monitoring **47**

4.2.1 Rain Gauge Data 48
4.2.2 Radar Rainfall 49

4.3 Hydraulic Monitoring Data Analysis and Its Use in Flow Component Development 52
4.3.1 Sli/icer 52
4.3.2 Dry Weather Flow Components 59
4.3.3 RDII – Rainfall Dependent Inflow/Infiltration 63
4.3.4 Ashburton Water Filtration Plant Discharges 65

4.4 Flow Balance Analysis 71
4.4.1 Dry Weather Flow 71
4.4.2 Wet Weather Flow 79

SECTION 5 – MODEL DEVELOPMENT 86

5.1 Model Network Construction 86
5.1.1 Macro Model to Micro Model 86
5.1.2 Representation of Engineered SSOs 86
5.1.3 Model Updates Based on Field Data 88
5.1.4 Pre and Post SC812 Relief Sewer Representation 89
5.1.5 Model Network Validation 91

5.2 Subcatchment Delineations 92

5.3 Flow Components 93
5.3.1 Groundwater Base Infiltration 95
5.3.2 Wastewater Per Capita Usage and Time Variations 95
5.3.3 Ashburton WFP Wastewater Discharge 96
5.3.4 RDII 97

5.4 Model Boundary Conditions 99

SECTION 6 – MODEL CALIBRATION AND VALIDATION 101

6.1 Model Calibration and Validation 101

6.2 Dry Weather Calibration 102
6.2.1 Event Selection 102
6.2.2 Dry Weather Calibration Parameters 103
6.2.3 Dry Weather Flow Calibration Evaluation 103

6.3 Wet Weather Calibration and Validation 111
6.3.1 Wet Weather Calibration Procedure 111
6.3.2 Input Data Quality and Model Parameter Sensitivity Checks 112
6.3.3 Wet Weather Calibration Evaluation 122
6.3.4 Wet Weather Calibration/Validation 131

6.4 Future Refinements 143
6.4.1 Assumptions for fine-tuning Calibration 143
6.4.2 Status of Field Inspection 144
6.4.3 Final Calibration and Validation 147

SECTION 7 – USE OF THE CALIBRATED HLSS MODEL **150**

7.1 Median R Wet-Weather Calibration **150**
7.1.1 Comparison of Metered and Modeled Results 152
7.1.2 QA/QC 153

7.2 Baseline Analysis and Capacity Assessment Report **154**

7.3 Alternative Analysis and Recommendations Report **155**

<u>Section</u>

APPENDICES

Appendix 1-A Dry Weather Observed vs. Predicted Plots
Appendix 1-B Dry Weather Observed vs. Predicted Statistics Table
Appendix 2-A Wet Weather Observed vs. Predicted Plots for Summer 2006 storms
Appendix 2-B Wet Weather Observed vs. Predicted Plots for Winter 2007 and Post-SC812 storms
Appendix 2-C Wet Weather Observed vs. Predicted Statistics Table
Appendix 3 Wet Weather Observed vs. Predicted Regression Plots

ATTACHMENT ON CD

Attachment 1 RDII vs. Rainfall Depth – PDF
Attachment 2 IWM File Containing the Calibrated InfoWorks Model
Attachment 3 Electronic Copy of the Model Development and Calibration Report

LIST OF FIGURES

Figure | Page

Figure ES-1. Goodness-of-fit plots at flow meter HL07 5
Figure ES-2. Processed summer (above) and winter (below) capture coefficients in HLSS 6
Figure ES-3. Sensitivity check with seasonal and year-round capture coefficients at HL33 for the November 16 storm 7
Figure ES-4. Simulated and observed maximum HGL along HLI for the November 16 storm 8
Figure ES-5. Simulated SSO locations for November 16th storm compared with recorded capacity-related SSO locations (2003 – 2007) 10
Figure 1-1. Baltimore Sewershed Study Boundaries 2
Figure 2-1. Location of HLSS boundary meters 6
Figure 3-1. InfoWorks CS User Interface 11
Figure 3-2. Non-linear Reservoir Conceptualization 12
Figure 3-3. Flow Components in Sanitary Sewer System 16
Figure 4-1. Period of system-wide flow monitoring in HLSS 22
Figure 4-2. Flow metering site sheet for HL38 23
Figure 4-3. New Flow Meters for the SC812 Relief Line 24
Figure 4-4. New Flow Meters on both ends of the HLI Siphon 24
Figure 4-5. Recurring and capacity-related SSO locations in HLSS 26
Figure 4-6. HLI Inverted Siphon profile 32
Figure 4-7. HLI profile from as-built drawing 33
Figure 4-8. Population Processing in GIS 34
Figure 4-9. Population density in HLSS based on Census 2000 35
Figure 4-10. Top 5 Water Users in HLSS with their water consumption 36
Figure 4-11. Sonar Inspection showing Sediment Depth at Pipe in High-Level Interceptor 40
Figure 4-12. Macro Model Overlaid on HLSS Micro Model Network 41
Figure 4-13. Aerial Photo Near Engineered SSOs 132, 134 and 135 45
Figure 4-14. Scattergraph for November 16th Storm at Engineered SSO134. 45
Figure 4-15. Scattergraph for November 16th Storm at HL33. 46
Figure 4-16. Rain gauge locations near HLSS 50
Figure 4-17. DDF Curves at three HLSS rain gauge locations for July 5th storm 51
Figure 4-18. DDF Curves at three HLSS rain gauge locations for Nov 16th storm 51
Figure 4-19. Radar Grid in HLSS 52
Figure 4-20. Flow data from May 2006 to May 2007 53
Figure 4-21. G*lobal settings in Sli/icer* 54
Figure 4-22. *Engineering Wizard with functions under Meter Sub-tab* 54
Figure 4-23. Rain tab with sub-tabs of Distribution, IDF Data, and Event Analysis. 55
Figure 4-24. Weekday and weekend diurnal pattern with dry day traces from Sli/icer 56
Figure 4-25. Wet weather components in Sli/icer to calculate RDII. 57
Figure 4-26. . Q vs. I Plot in Sli/icer 58
Figure 4-27. Scattergraph at HL16 with surcharges 59
Figure 4-28. Scattergraph at HL07 with SSO events 59
Figure 4-29. *Dry Day table display from Sli/icer* 62

Figure 4-30. Weekday and Weekend average diurnal pattern for Summer 2006, Winter 2007 and Summer2007 for HL37.....63
Figure 4-31. RDII volume vs. Rainfall depth for HL39.....64
Figure 4-32. Seasonal capture coefficient in Sli/icer from Q vs. I analysis.....65
Figure 4-33. Ashburton Water Filtration Plant in HLSS.....66
Figure 4-34. Sedimentation Basin in Ashburton WFP.....67
Figure 4-35. Reproduced Sed-Basin Discharge Pattern.....67
Figure 4-36. Gabion structure in the Washwater Lake.....69
Figure 4-37. Discharge from Washwater Lake for the period of September 5-8, 2008.....69
Figure 4-38. Circular chart showing discharge from Washwater Lake pumps from December 15-22, 2005.....70
Figure 4-39. Dry weather flow propagation in HLSS and meters with flow imbalance on August 15th (above) and December 7th (below).....72
Figure 4-40. Good flow meters in HLSS where total DWF rate and BI/WWP decomposition in Sli/icer are both reasonable.....73
Figure 4-41. Process for Calculating DWF Parameters.....75
Figure 4-42. Summer 06 HLSS calibration meters (above) and processed DWF parameters for model use (below).....76
Figure 4-43. Winter 07 HLSS calibration meters (above) and processed DWF parameters for model use (below).....77
Figure 4-44. Summer 07 HLSS calibration meters (above) and processed DWF parameters for model use (below).....78
Figure 4-45. Winter 07 Gross versus net RDII for HL20-24.....79
Figure 4-46. Graphical representation of net RDII calculation process.....81
Figure 4-47. Graphical representation of original and processed gross RDII.....81
Figure 4-48. RDII imbalance.....82
Figure 4-49. Graphical representation of gross RDII for HL36 and HL37.....83
Figure 4-50. Graphical representation of original and processed RDIIs for HL36 and HL37.....83
Figure 4-51. Processed summer (above) and winter (below) capture coefficients in HLSS.....85
Figure 5-1. Example Locations where 8” Pipes were Added to the Model Extent.....87
Figure 5-2. Macro-model Extent (shown in Red) on the HLSS Micro-model Network.....87
Figure 5-3. Engineered SSOs in Model Extent and an Example Model Setup for SSO 132.....88
Figure 5-4. Sewer Network near Washwater Lake A) before and B) After SC812 was Installed.....90
Figure 5-5. SC-812 diversion chamber drawing.....91
Figure 5-6. Model Setup for the SC812 Representation.....92
Figure 5-7. Example of Subcatchment Delineation in InfoWorks.....94
Figure 5-8. Inflow points for Ashburton WFP Discharges.....96
Figure 5-9. Conceptual diagram of summer and winter RDII generator in the model.....99
Figure 5-10. Linear Interpolation to fill in Missing Data.....100
Figure 6-1. Profile of the Upper Gwynns Run Interceptor (GRI).....104
Figure 6-2. Profile of Lower GRI.....105
Figure 6-3. Profile of second Gwynns Run Interceptor (GRI).....106
Figure 6-4. Profile of the High Level Interceptor (HLI) and accumulated sediment profile along the HLI.....107
Figure 6-5. Modeled versus Observed for Average Dry Weather Flow for August 11 - 22.....109
Figure 6-6. Modeled versus Observed for Average Dry Weather Flow for December 4 - 12.....110
Figure 6-7. Radar vs. Rain gauge data at each point location.....113
Figure 6-8. Radar (HL40) vs. Rain gauge (GF-09).....114

Figure 6-9. Radar (HL30) vs. Rain gauge (GF-07) ... 114
Figure 6-10. Radar (HL09) vs. Rain gauge (JF-12) ... 115
Figure 6-11. Radar vs. RG at HL37 for June 2 storm ... 116
Figure 6-12. Radar vs. RG at HL33 for June 2 storm ... 116
Figure 6-13. Radar vs. RG at HL41 for June 25 storm ... 117
Figure 6-14. Radar vs. RG at HL32 for June 25 storm ... 117
Figure 6-15. Sediment Profile from S35CC_005MH to S35AA_023MH ... 118
Figure 6-16. Sediment depth sensitivity results for November 7th storm at HL18 flow meter - one with maximum (green) and the other with average (red) depth. ... 119
Figure 6-17. Debris found between S33C__014MH and S33C__029MH ... 119
Figure 6-18. Debris found between S33A__021MH and S33AA_014MH ... 120
Figure 6-19. Sensitivity check with seasonal and year-round capture coefficient at HL33 for November 16 storm. ... 121
Figure 6-20. Sensitivity check with seasonal and year-round capture coefficient at HL19 for November 16th storm. ... 122
Figure 6-21. Profile of the Upper Gwynns Run Interceptor (GRI) ... 123
Figure 6-22. Profile of the Lower Gwynns Run Interceptor (GRI) ... 124
Figure 6-23. Frequent surcharge at HL25 after SC-812 was put in service ... 125
Figure 6-24. Profile of the Lower Gwynns Run Interceptor (GRI) ... 126
Figure 6-25. Profile of the High level Interceptor (HLI) and accumulated sediment profile ... 127
Figure 6-26. Simulated and observed maximum HGL along HLI for July 5th storm ... 132
Figure 6-27. Simulated and observed maximum HGL along HLI for November 16th storm ... 133
Figure 6-28. Simulated lost volumes from engineered SSOs for November 16 storm ... 135
Figure 6-29. Evidence of overflow for engineered SSO 55, 56, and 57 between May 2003 and May 2007. ... 136
Figure 6-30. Evidence of overflow for engineered SSO 126, 131, and 130 between May 2003 and May 2007. ... 137
Figure 6-31. Simulated SSO locations for November 16th storm compared with recorded capacity-related SSO locations (2003 – 2007) ... 140
Figure 6-32. Flow Meter schematic of HLS1 and HLS2 ... 141
Figure 6-33. Hydrographs at HLS1 (upstream of the siphon) and HLS2 (downstream of the siphon) for September 28th storm in 2008 ... 142
Figure 6-34. Status of land survey and manhole inspection for model manholes ... 146

LIST OF TABLES

Table | Page

Table 2-1. Dry and Wet Weather Flow Rate Range from HLSS Boundaries 8
Table 4-1. HLSS flow meter installation history 21
Table 4-2. Capacity-Related SSO Records in HLSS 27
Table 4-3. List of Engineered SSOs in HLSS 43
Table 4-4. List of Flow Monitored Engineered SSOs. 44
Table 4-5. Storm period and depth for global storms 48
Table 5-1. User Defined Flags in InfoWorks Referring the Data Source. 89
Table 5-2. Inflow Assignment Types in InfoWorks 94
Table 5-3. Depression Storage, Capture Coefficient Values for Summer and Winter Study Periods in InfoWorks. 98
Table 6-1. Proposed Dry Weather Flow Calibration Events 102
Table 6-2. Wet weather flow calibration events 111
Table 6-3. Parameters for wet weather flow calibration, and their uses for HLSS model calibration. 112
Table 6-4. Wet weather flow calibration evaluation 128
Table 6-5. Lost volume and peak flow through engineered SSO 134
Table 6-6. Simulated SSO volume for July 5th and November 16th storm 138
Table 6-7. Number of contradiction in pipe size from different data 143
Table 6-8. Smoke tested basins as of December 2008 147

EXECUTIVE SUMMARY

The City of Baltimore's aging sanitary sewer system is overburdened with urbanization, growing population, excessive inflow and infiltration (I/I), and structural defects that have resulted in surcharging and sanitary sewer overflows during moderate to large storm events. The City has undertaken a Collection System Evaluation and Sewershed Planning process to eliminate sanitary sewer overflows (SSO) and combined sewer overflows (CSO) and rehabilitate the collection system in accordance with the requirements of a consent decree (CD) entered into by the City, US Environmental Protection Agency (EPA) and the State of Maryland Department of the Environment (MDE). The City has divided its entire drainage area into eight sewershed basins, with eight consultant teams working concurrently with the project and technical management teams to conduct sewershed studies for the entire Baltimore collection system.

Among the eight teams, the JMT/ADS joint venture (1028) is leading the rehabilitation study for the High Level Sewershed (HLSS). As part of the effort, hydraulic models of eight collection systems are required to be developed and the models will be used to evaluate the proposed system modifications, upgrades, and expansions undertaken to enhance the overall system conveyance capacity. HydroQual is working with JMT/ADS to conduct the hydraulic modeling analysis of HLSS using the City's selected modeling software, InfoWorks CS.

This report details the model development and calibration tasks performed by the HLSS team. Two separate documents were provided by the City, namely, the CD and a Baltimore City Sewershed Evaluation Study (BaSES), that provide general guidelines for model network development, flow data analysis, and adequacy of calibration. The purpose of this report is to: (1) summarize the various data sources and analyze the pertinent data to support model calibration, (2) describe the model development process including physical model construction and flow data inputs, emphasizing any deviations from the guidelines outlined in BaSES manual, (3) document the calibration procedures adopted by the HLSS team and compare the modeled and observed data to demonstrate the calibration adequacy in accordance with the CD and BaSES guidelines, (4) identify some of the system-specific hydraulic bottlenecks in HLSS, and (5) review some model refinements that can accurately reflect the actual field conditions and to characterize the specific inflow and infiltration sources to guide the sewer system rehabilitation efforts.

The HLSS includes a drainage area of approximately 4,600 acres served by separate storm and sanitary sewers. The majority of HLSS drainage area is residential, with a total population of about 100,000. This system has two major interceptors, the Gwynns Run Interceptor (GRI) that collects flows from the northwest portion of the drainage area, and High Level Interceptor (HLI) that serves the southern portion. The HLSS interacts with a number of other sewersheds, which complicates the system hydraulic conditions during moderate or large rain events.

Following the City's suggested modeling procedures specified in BaSES and the CD, the construction of HLSS hydraulic model began with a review of the City's macro model developed and provided by the technical management team, in which sewers 12 inches and larger were included. The macro model was expanded by the HLSS team using the City's GIS database to include sewers that were 10 inches and larger and any additional eight-inch sewers necessary to evaluate the known capacity-related issues in HLSS. Consequently the model network included historical SSO locations and engineered SSOs in accordance with the CD requirements. The expanded model is known as the micro model of the HLSS.

During model construction, the newly collected data from on-going field surveys was used to update the model upon validation by JMT/ADS. These included: (a) manhole X and Y coordinates obtained from land surveys; (b) manhole rim elevations, pipe inverts, and pipe diameters confirmed during manhole inspections; and (c) sediment depths observed during sonar inspections. The HLSS portion of the City's GIS database was also updated using the same data, so that the database and model had consistent information and could be linked to facilitate any future asset management efforts by the City. During the primary flow monitoring period, a new interceptor relief sewer (SC812) was constructed by the City to provide relief to the Upper Gwynns Run Interceptor. In order to capture any alteration in hydraulic conditions, two separate InfoWorks model networks were setup to represent the pre and post-SC812 construction conditions. The two model networks were identical except for the elements that represented changes in physical conditions of the existing and relief sewers. The final HLSS micro model network includes approximately 1,000 model nodes (manholes, pumps, etc.) and links (pipes).

The City conducted a comprehensive system-wide flow monitoring program to collect continuous hydraulic data at approximately 350 locations throughout the sanitary sewer system. The primary flow monitoring program for HLSS ran from May 2006 to May 2007 at 42 locations, five of which measured flows at boundary locations representing interactions with the other sewersheds. Eleven of the HLSS meters are still active as part of the City's long-term monitoring plan. In addition, four flow meters were added in 2008 to provide data upstream and downstream of SC812 and two other meters to evaluate the hydraulic capacity of the HLI inverted siphon. Coupled with the flow monitoring program, the City installed 20 rain gauges to collect rainfall data at short-time intervals and the data from three of those gauges were used for the I/I evaluation in HLSS. Furthermore, the City provided rain gauge adjusted Doppler Radar-rainfall data to the consultant teams for better characterization of the spatial rainfall variability within each sewershed.

The monitored flow and rainfall data was reviewed and analyzed by the HLSS team using the City-selected Sli/icer.com program. This data analysis tool characterizes sewer system performance during dry and wet weather conditions, and also the development of necessary inputs for the micro hydraulic model. Sli/icer is a web-based I/I analyses software developed by ADS, which provides various data visualization and processing functions. Using Sli/icer.com, the team assessed the quality and adequacy of monitoring data at each flow basin, and pursued efforts to minimize any uncertainty resulting from poor data quality by making technically sound assumptions and adopting statistical and analytical tools to resolve any issues.

The team conducted a dry weather flow decomposition analysis to estimate the fractions of each flow component (groundwater base infiltration; wastewater production from residential areas; discharges from large municipalities, and industrial and commercial facilities) and their diurnal variations in each monitored basin. For the wet weather rainfall dependent inflow and infiltration (RDII) analysis, the seasonally varying capture coefficient and initial loss value for each flow basin were estimated using regression analysis of the rainfall depth and measured RDII volume based on 29 global storms identified in the monitoring period. In addition, the influences of other sewershed flow contributions on the HLSS were accounted for through processing the data monitored at the boundary meters and developing the appropriate time-series inputs. The flow discharge rate and variations of the largest flow contributor to HLSS, the Ashburton Water Filtration Plant (WFP), were found by processing data measured at the closest metering location. The HLSS team also visited the plant and consulted with the plant operators and design engineers to obtain the data needed to characterize the discharge and its representation in the model.

In the HLSS model, flow basins were divided into a total of 321 subcatchments in order to accurately represent the flow entry into sewers under both dry and wet weather conditions. The HLSS team followed delineation guidelines recommended in the City's BaSES manual. The parameters developed from dry and wet weather data assessment processes were used as initial values in the HLSS micro model and adjusted as needed during model calibration.

Following BaSES guidelines, the HLSS micro model calibration/validation was performed in two steps - initially for the dry weather conditions and then for wet weather. The purpose of DWF calibration/validation was to develop accurate flows that attribute to ground base infiltration, base wastewater flow from residential areas and industrial/commercial dischargers in the sewer system. Then the accuracy of RDII modeling was optimized through the calibration/validation of model performance during rain events.

For DWF calibration, six events were selected among the three seasons of study (Summer 2006, Winter 2007 and Summer 2007) and the pre and post-SC812 conditions to support dry weather calibration. The primary rationale for selecting those events was to choose dry periods with no rainfall for at least 48 hours prior to the event so that there would be little to no residual moisture that might affect infiltration during these periods. The duration of dry events ranged from 5 to 12 days in order to characterize the possible variations between the weekday and weekend water usage patterns, again in accordance with the BaSES guidelines.

During model calibration, parameters such as pipe size, sediment depth, roughness, and slopes were checked and adjusted only when the field data sources revealed discrepancies. Using time-series plots of simulated and observed flow, depth and velocity at each flow meter were generated for each event and the average flow rate between simulated and observed data on a system-wide basis was used to assess the adequacy of model calibration. The model performance in terms of correlation between monitored and modeled data was very good at most of the locations for flow, depth and velocity.

The RDII analysis using Sli/icer revealed that the amount of RDII per unit rainfall depth, or capture coefficient, in winter was larger than that found in summer, and the seasonal difference was significant for several basins in HLSS. Therefore, wet weather flow calibration was conducted using three different InfoWorks model networks - for summer 2006, winter 2007, and summer 2007. For the winter 2007 network, additional RDII was brought into the system while the physical model was kept exactly the same as summer 2006 network. The Summer 2007 network, which included SC812, had the same RDII characteristics as the winter 2007 network since the period had only a few storms available in March and April.

Wet weather flow calibration was conducted for all global storms for which Radar rainfall data were provided by the City's technical management team, 1015. The runoff routing value was used as the primary calibration parameter, while the catchment width and slope were used as supplemental parameters. Capture coefficient and depression storage, derived from Sli/icer, were used as fixed parameters in the RDII analysis. Calibration results were evaluated using time-series plots for flow, depth, and velocity; and a goodness-of-fit plot. Specific model calibration criteria for wet weather flow calibration, as suggested in BaSES manual, include the following:

- Modeled peak flow rate should be within -10% and +25% of the observed peak rate;
- Modeled volume of flow should be within +20% and -10 % of the observed;
- Modeled depth of flow in surcharged sewers should be within +18 inches and -4 inches in sewers 21 inches in diameter and larger (and within +6 inches and -4 inches in sewers smaller than 21 inches in diameter) of the observed;

- Modeled depth of flow at unsurcharged critical points in the system, i.e., at SSO structures, should be within 4 inches of the observed; and
- Shape and timing of the hydrographs should be similar.

In order to assess whether the calibrated model satisfied the criteria for each metered location, the HLSS team generated goodness-of-fit plots to compare simulated and observed values for peak flow, flow volume, peak depth, and peak time. Figure ES-1 shows an example of goodness-of-fit plots for flow meter HL07 located closer to the downstream end of the HLI. The calibration criteria for peak flow rate, volume, and surcharge depth are represented as dotted lines (on either side of the 45-degree line that represents a perfect correlation between the two). This provides a visual check to see if the model results meet the criteria for most of the storms. Observations on this correlation between modeled and monitored data is also summarized in a separate table in the report, especially for locations where these criteria are not satisfied. For HL07 shown in Figure ES-1, for example, the modeled values meet the above BaSES-criteria for most events.

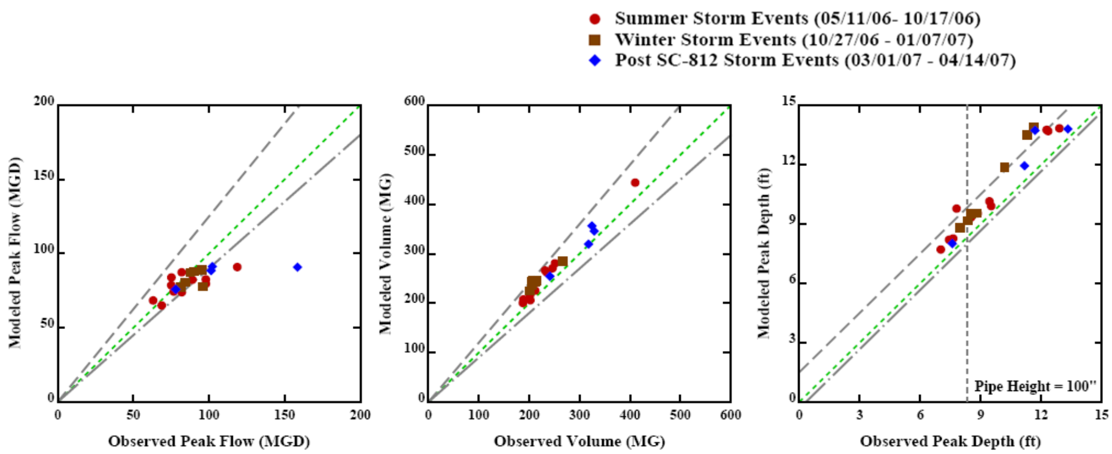


Figure ES-1. Goodness-of-fit plots at flow meter HL07

The adequacy of wet weather flow calibration was assessed by the HLSS team using two additional metrics: SSO locations and maximum hydraulic grade line (HGL). Two large storms, namely, those on July 5 and November 16, were selected from the primary monitoring period. These are equivalent to a 2-year 24-hour storm severity. The potential SSO locations revealed from the simulation results of these two storms were compared with the historical SSO locations, and the simulated maximum HGLs along HLI were compared with observed data at each flow metering location. The model results correlated very well with observed data in the entire system. The major findings from model calibration and validation are summarized here.

Seasonal Variation in RDII Severity:

The capture coefficient estimation in Sli/icer does not work accurately for systems with irregular discharges such as pumps. In HLSS, there is a significant irregular discharge from the Washwater Lake through multiple pumps, which made the estimation of the capture coefficient quite complex along the GRI downstream of Washwater Lake and HLI. Therefore, the capture coefficients for these interceptor basins were pre-determined as the average of other HLSS basins and further adjusted during calibration. Except for these basins along the GRI and HLI, the capture coefficient was calculated for the summer/winter seasons from Sli/icer. Figure ES-2 shows the processed capture coefficients except for the interceptor basins downstream of HL28 for summer and winter. The figure was color coded from light blue to dark blue based on the severity of I/I as indicated by higher capture coefficients. Two observations were derived here based on the HLSS data analysis:

- RDII was more severe for flow basins contributing to the upstream portion of GRI
- RDII was more severe in winter than in summer for the whole HLSS

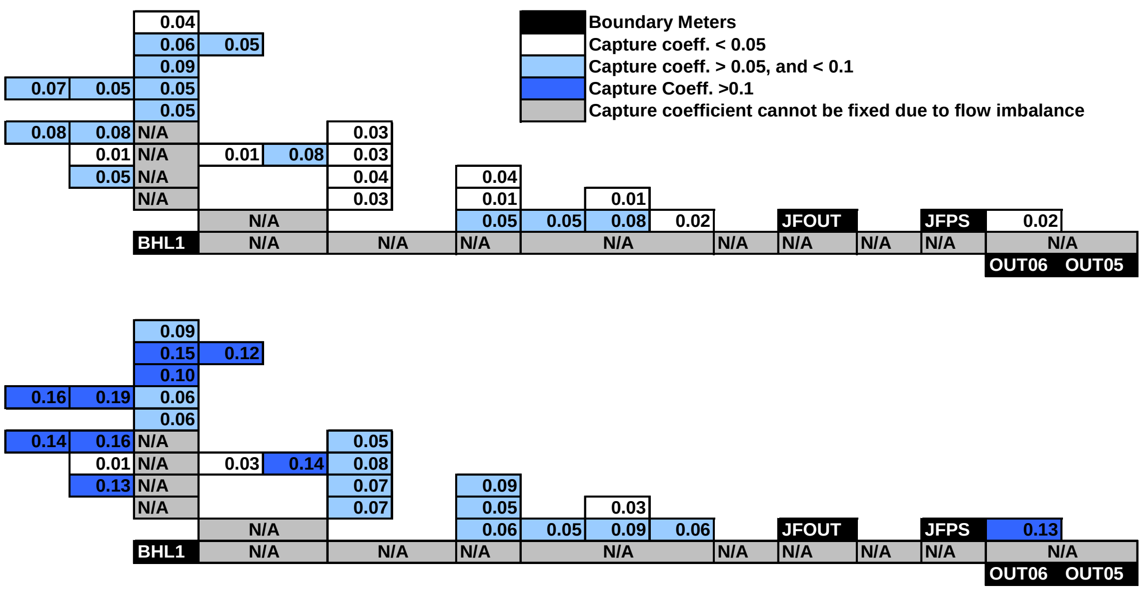


Figure ES-2. Processed summer (above) and winter (below) capture coefficients in HLSS

For each of the three Infoworks model networks, different configurations were setup to include seasonally-varying capture coefficients although the physical configurations were very similar (except for the pre and post-SC812 conditions). For each model subcatchment, single runoff surface was utilized to represent the summer RDII conditions. Another runoff surface was utilized with the existing summer runoff surface to represent the increased winter RDII. This seasonal add-on runoff surface worked very well at most flow metering locations, especially where the winter RDII was much larger than in summer. Figure ES-3 shows a comparison of model performance when the seasonal capture coefficients are used instead of a single year-round capture coefficient derived from all the data lumped together. At the HL33 flow meter, both surcharge depth and flow rate correlated better with the monitored data when using the winter capture coefficient (instead of a year-round value) for the November 16 storm which is one of the large events closer to a 2-year design storm severity.

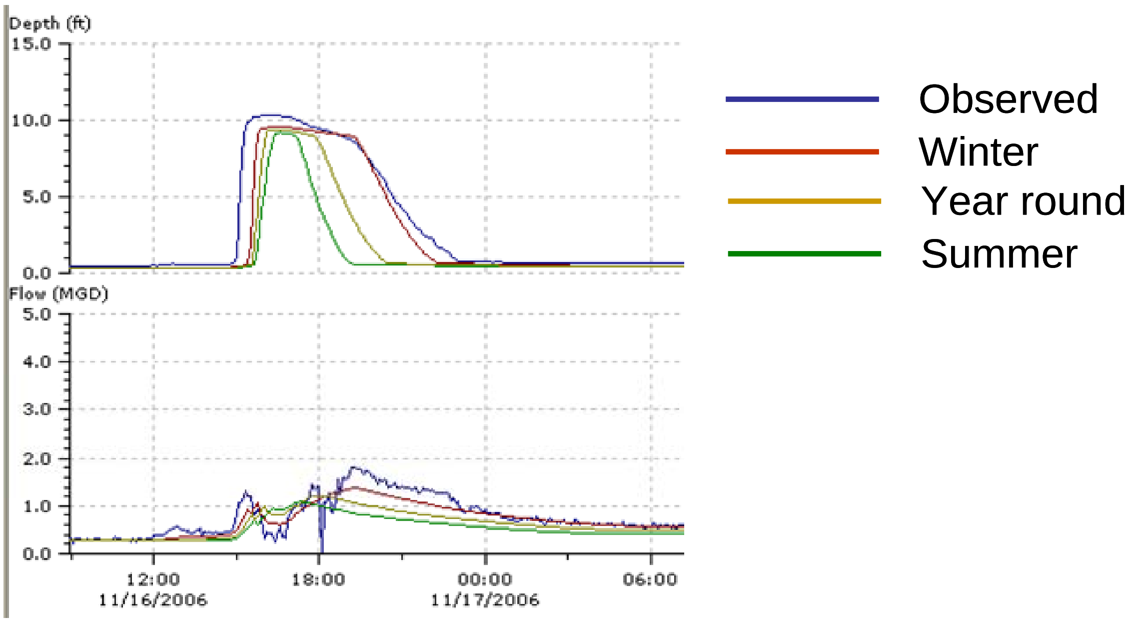


Figure ES-3. Sensitivity check with seasonal and year-round capture coefficients at HL33 for the November 16 storm

Model calibration was initially conducted using the two different models for summer and winter in order to reproduce the corresponding RDII and delayed infiltration volumes observed in the monitoring data. The technical management team provided guidance to the HLSS Team to combine the summer and winter models into an all-year model using Median R capture coefficient. The intent was to maintain consistency among various sewershed studies in the City and to ensure that the City-wide macro model is compiled from individual sewershed models that use the same basis. In order to fulfill this requirement from the City, the HLSS Team calculated median values of summer and winter for both depression storage and capture coefficient and used for the Median R model development. The Median R model was further calibrated so that the model could reproduce the RDII behavior and SSO occurrences well for larger storm events which were used for subsequent reports: the Baseline Analysis and Capacity Assessment Report and Alternatives Analysis and Recommendation Report.

Sediment in HLI and its surcharge during wet weather:

Sonar inspections were conducted for 18,000 linear feet of the High Level Interceptor. This covered approximately 75% of HLI, and the debris data significantly enhanced the model accuracy of surcharge depths along HLI. Figure ES-4 shows the maximum HGL for the November 16 storm, with the maximum observed hydraulic depth at each flow meter along HLI. Also shown with green circles are the manhole locations where the maximum HGL was closer to their rim (ground) elevations, which indicates the potential for a SSO.

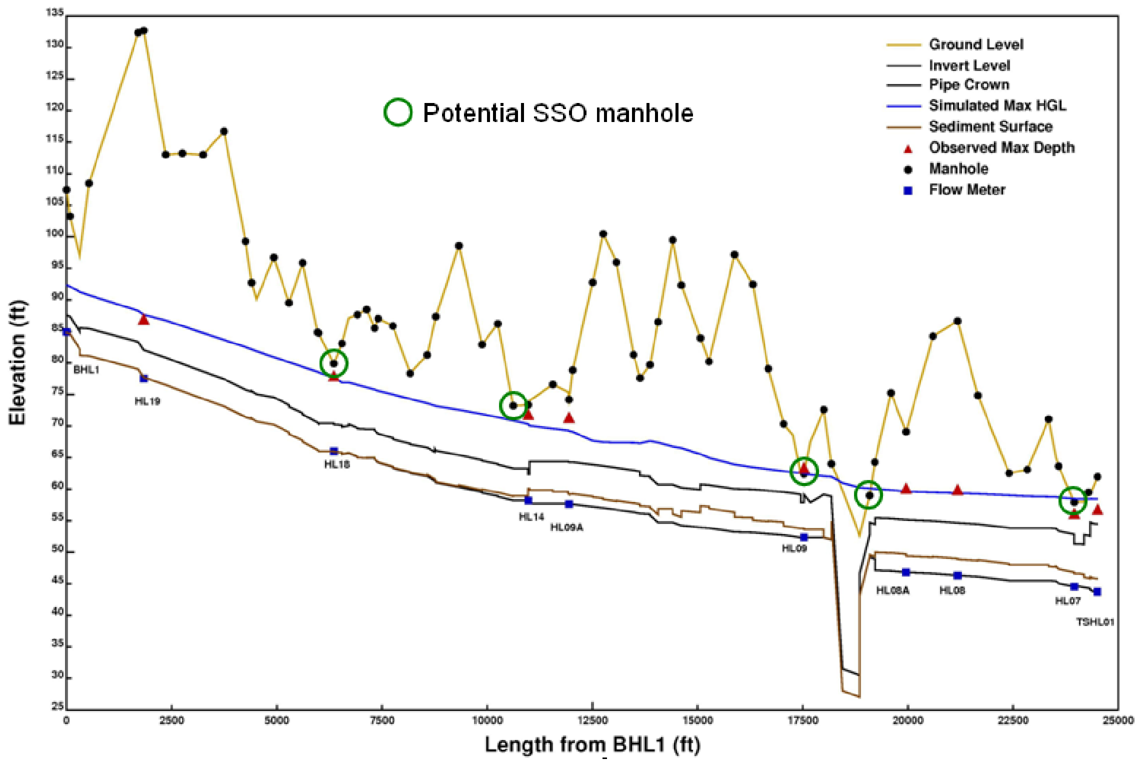


Figure ES-4. Simulated and observed maximum HGL along HLI for the November 16 storm

SSO volume in HLSS:

In the model validation process, the locations with a history for overflow were compared with the model-predicted SSO locations. The City's data for capacity-related overflows that occurred between 2003 and 2007 were reviewed by the HLSS team. Figure ES-5 shows the simulated SSO locations for the November 16 storm and corresponding SSO volumes with historical SSO locations. Simulation results revealed that there were several overflow manhole locations along upper GRI, including the 1200 Dukeland Street manhole at the upstream end of SC812. Capacity-related SSO locations along GRI and near the HLI inverted siphon (known as the Baltimore City Detention Center SSO) were well reproduced by the hydraulic model.

Although the HLSS model has been satisfactorily calibrated to meet the BaSES and HLSS-defined metrics, it will need to be further refined with recent field investigations and flow monitoring data prior to evaluating future rehabilitation alternatives. The following locations, with a history of surcharging and overflows, will be specifically reviewed and refined in the near future:

- Active engineered SSOs near Liberty Heights Avenue
- Lower GRI
- HLI inverted siphon

In addition to these key locations, the CCTV data and smoke testing data (being collected by the HLSS team) will be reviewed and analyzed on a system-wide basis. Inflow type defects found in CCTV will be incorporated in the model as additional I/I sources on linear-foot basis. The rooftop connections identified by smoke testing can be incorporated at impervious area contributing 100% of runoff as RDII. For major structural pipe defects found in CCTV, the total number of such defects can be counted within HLSS flow basins and correlated to the capture coefficients determined from the Sli/icer analyses. Upon providing the appropriate representation of these field conditions in the model, the potential benefits of pipe rehabilitation or rooftop/catchbasin disconnections can be evaluated during alternative analysis.

An example of such field data is sediment profile along HLI, which has already been used effectively in enhancing prediction accuracy during this model calibration process. The calibrated model can then be used for evaluating alternatives such as heavy or partial cleaning of HLI. Therefore, the HLSS team recommends that the model refinements be performed with recent field data in order to effectively evaluate alternatives so that a cost-effective rehabilitation strategy can be developed for the HLSS system.

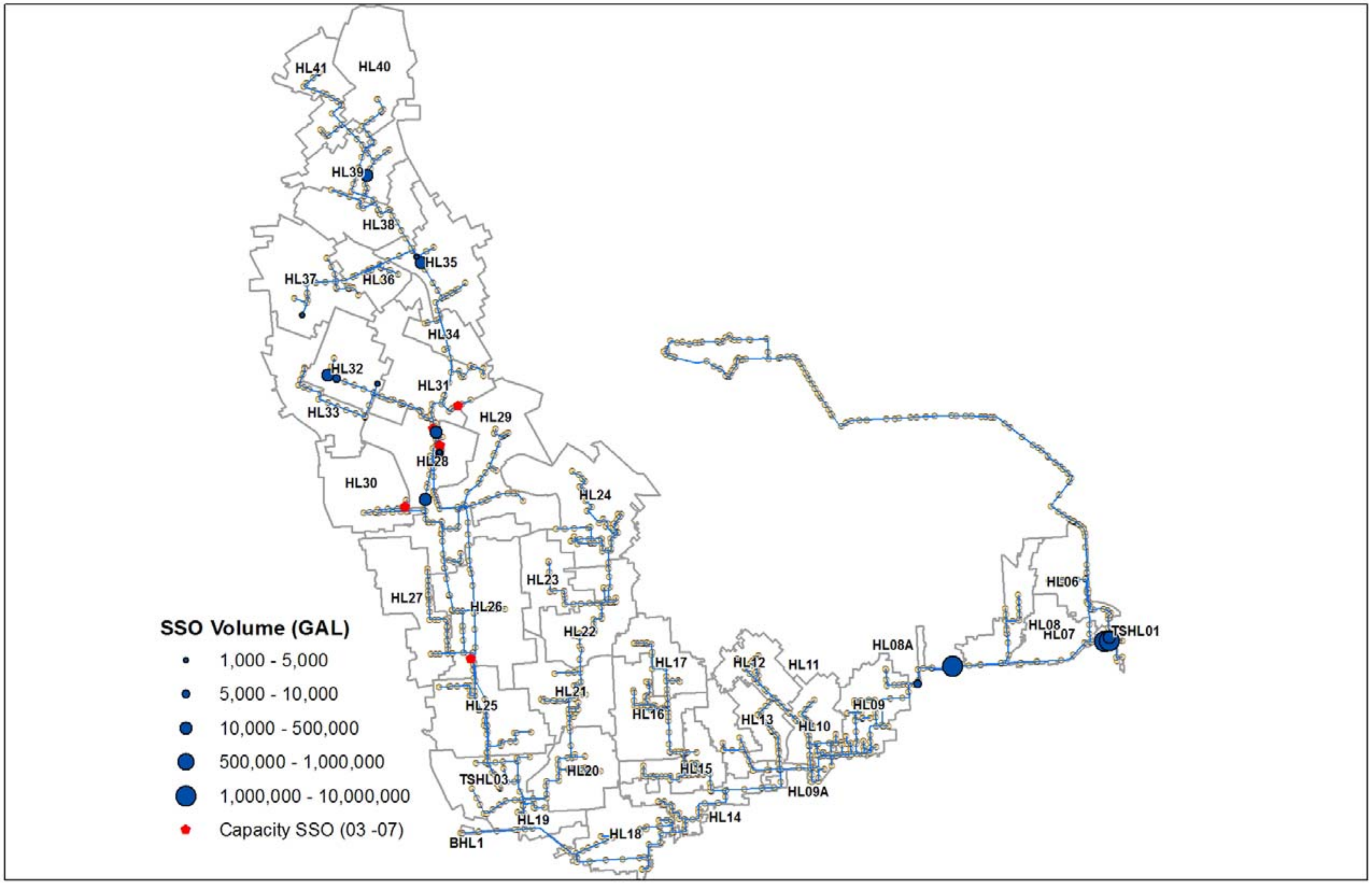


Figure ES-5. Simulated SSO locations for November 16th storm compared with recorded capacity-related SSO locations (2003 – 2007)

SECTION 1 - INTRODUCTION

1.1 BACKGROUND

The City of Baltimore (referred to herein as the City of Baltimore) owns and operates hundreds of miles of separate storm and sanitary collection systems that serve approximately 600,000 people. A small fraction of the system consists of combined sewers, and the pertinent regulatory issues are dealt with in a separate permitting process. The aging sanitary sewer system has been overburdened with urbanization, growing population, excessive inflow and infiltration (I/I) during and after wet weather, and structural defects that have resulted in surcharging and sanitary sewer overflows during moderate to large storm events. On September 30th 2002, the City and the United States Environmental Protection Agency (EPA) entered into a consent decree (CD) with the purpose of establishing necessary measures that enable Baltimore to comply with the Clean Water Act and the State of Maryland Department of the Environment's regulatory requirements. This CD requires the City to eliminate sanitary sewer overflows (SSO) and combined sewer overflows (CSO), to conduct a Collection System Evaluation and Sewershed Planning process, and to rehabilitate the aging sewers and facilities. Paragraph 12 of the CD specifically requires Baltimore to develop dynamic hydraulic models of the various collection systems, and use the models to evaluate potential improvements from the ongoing I/I rehabilitation projects, proposed system modifications, upgrades, and expansions undertaken to enhance the conveyance capacity and overall performance of the collection system.

The City divided its entire separately-sewered drainage area into eight sewershed basins, namely, Dundalk, Gwynns Falls, Herring Run, High Level, Jones Falls, Low Level, Outfall, and Patapsco, as shown in Figure 1-1. Eight different consultant teams worked concurrently with the project management (1014) and technical management (1015) teams to conduct sewershed studies for these eight basins. Many of these basins are inter-related and the City's overall approach is to study each of these basins independently, and establish boundary condition linkages at the interfaces through macro model or regional model. The technical consultant, 1015, is charged with the responsibility of developing an overall city-wide model of the system (termed as the "regional model") by integrating all the sewershed models (termed as "micro models") independently being developed by the eight consultant teams.

The ADS/JMT joint venture (1028) is leading the High Level Sewershed (HLSS) rehabilitation study. HydroQual is working as the hydraulic modeling sub-consultant for this project. The joint venture is leading other study tasks and the overall project management.

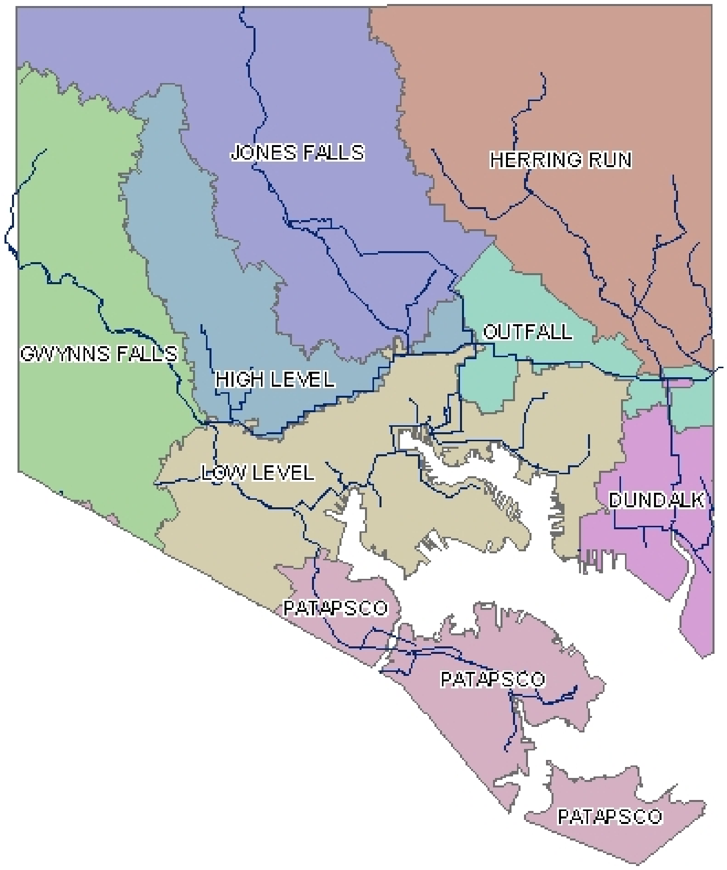


Figure 1-1. Baltimore Sewershed Study Boundaries

The joint venture is leading tasks such as development of a work plan, project coordination by delegating and overseeing the work of various sub-consultants, cost and schedule controls, monthly progress reports and meeting materials, coordination of submittals to the City and establishment of the engineering quality control and assurance. All data pertaining to the HLSS study such as flow metering data, rainfall data, manhole inspections, survey data, CCTV, smoke testing, dye water testing, GIS database of sewage collection plans, as-built drawings, SSO records, and previous reports and studies have been collected by 1028. These data were utilized by HydroQual for constructing and calibrating the HLSS hydraulic model. The 1028 team is also conducting quality assurance/quality control (QA/QC) of the data in accordance with the City's data quality testing procedures and, when completed, those data will be used for updating the dynamic hydraulic model.

1.2 MODELING OBJECTIVES

HydroQual is supporting 1028 in fulfilling the CD's modeling requirements for the High Level sewershed. In order to maintain consistency in technical approaches used by the eight consulting firms, the 1014 and 1015 teams have established guidelines in the Baltimore Sewer Evaluation Standards (BaSES) Manual. The overall approach is to build the model in accordance with the requirements outlined in the CD and calibrate/validate that model while adhering to the guidelines provided in the BaSES manual. Long-term monitoring data compiled by the City is used to support this task, however, short-term additional or extended flow monitoring is recommended where necessary to enhance our system understanding so that appropriate management strategies can be proposed during the alternatives evaluation. Specific modeling objectives for this study, as stated in Consent Decree, is to evaluate the impact of 1) I/I rehabilitation projects, 2) proposed system modifications, 3) upgrades, and 4) expansions to the transmission capacity and performance of the collection system.

The City has chosen InfoWorks CS as the uniform modeling software for characterizing the sewer systems and conducting citywide I/I studies. Specific guidelines provided in the BaSES manual will be used to select appropriate modeling parameters in the InfoWorks suite and assess the model calibration adequacy. The InfoWorks Version 8.5.0 was used throughout the model construction, calibration/validation and application of the model to evaluate the current sewer capacity, estimate the extent of I/I, and to conceptualize I/I rehabilitation strategies for certain design storms and select the appropriate and cost-effective alternatives.

1.3 REPORT ORGANIZATION

The technical background and details for dynamic hydraulic modeling of the HLSS system are organized as follows. A description of the sewershed and modeling extent are provided in Section 2, which is followed by Section 3 which provides an introduction of the general modeling framework as well as the specific modeling tool and procedure used in the HLSS project. In Section 4, various data sources that have been used to develop and calibrate the model are listed. It also describes the analyses of monitored rainfall and flow data, along with a discussion on the data uncertainty. Section 5 documents the model network construction and input data development. The model calibration and validation processes are discussed in Section 6, including the selection of calibration/validation periods, sensitivity of modeling parameters, as well as the evaluation of results. Subsequently, Section 7 briefly describes two immediate uses of the model, namely, the baseline analysis and capacity assessment and future alternatives evaluation.

SECTION 2 – HIGH LEVEL SEWERSHED

2.1 SEWERSHED DESCRIPTION

The High Level Sewershed (HLSS) is one of eight sewersheds that constitute the conveyance system within the City of Baltimore and its interfacing with Baltimore County's system. HLSS has a drainage area of approximately 4,600 acres served by separate storm and sanitary sewers. The majority of HLSS drainage area is residential, with a total population of about 100,000 based on the 2000 census data. This drainage area generally slopes in the north-south direction with higher ground elevations in the northern portions (Figure 2-1).

The flows from the northwest portion of the HLSS drainage area are collected by the Gwynns Run Interceptor (GRI), which in turn, joins the larger main interceptor called the High Level Interceptor (HLI) at the south end of GRI. The HLI runs from west to east receiving small flow contributions from the High Level Sewershed in the upstream reach, and from the Jones Falls and Low Level Sewersheds in the downstream reaches. The HLI becomes the Outfall interceptor at the beginning of Outfall Sewershed and the Outfall Interceptor eventually conveys flow to the Back River Wastewater Treatment Plant (WWTP) for treatment and disposal to the Baltimore Harbor.

The HLI exhibits complex hydraulic conditions due to interactions with the other sewersheds. In addition, the conveyance capacities of GRI have been affected due to significant variations in flows during dry/wet weather induced by significant discharge from Ashburton Water Filtration Plant (WFP). These specific flow contributions are described in the following sections.

2.2 INTERACTIONS WITH OTHER SEWERSHEDS

As described above, the HLI has several inflow contributions from other sewersheds, and those flows can be quite significant during dry and wet weather periods. The inflow and infiltration flows from other sewersheds, in addition to those generated within HLSS, have posed excessive surcharging and some overflows within the HLSS drainage area. As part of the City of Baltimore's comprehensive capacity assessment and rehabilitation process, several flow metering locations were established to specifically quantify the flow contributions from these sewersheds.

The location of flow meters to measure these boundary flows are shown in Figure 2-1, and their dry and wet weather flow rate ranges are summarized in Table 2-1.

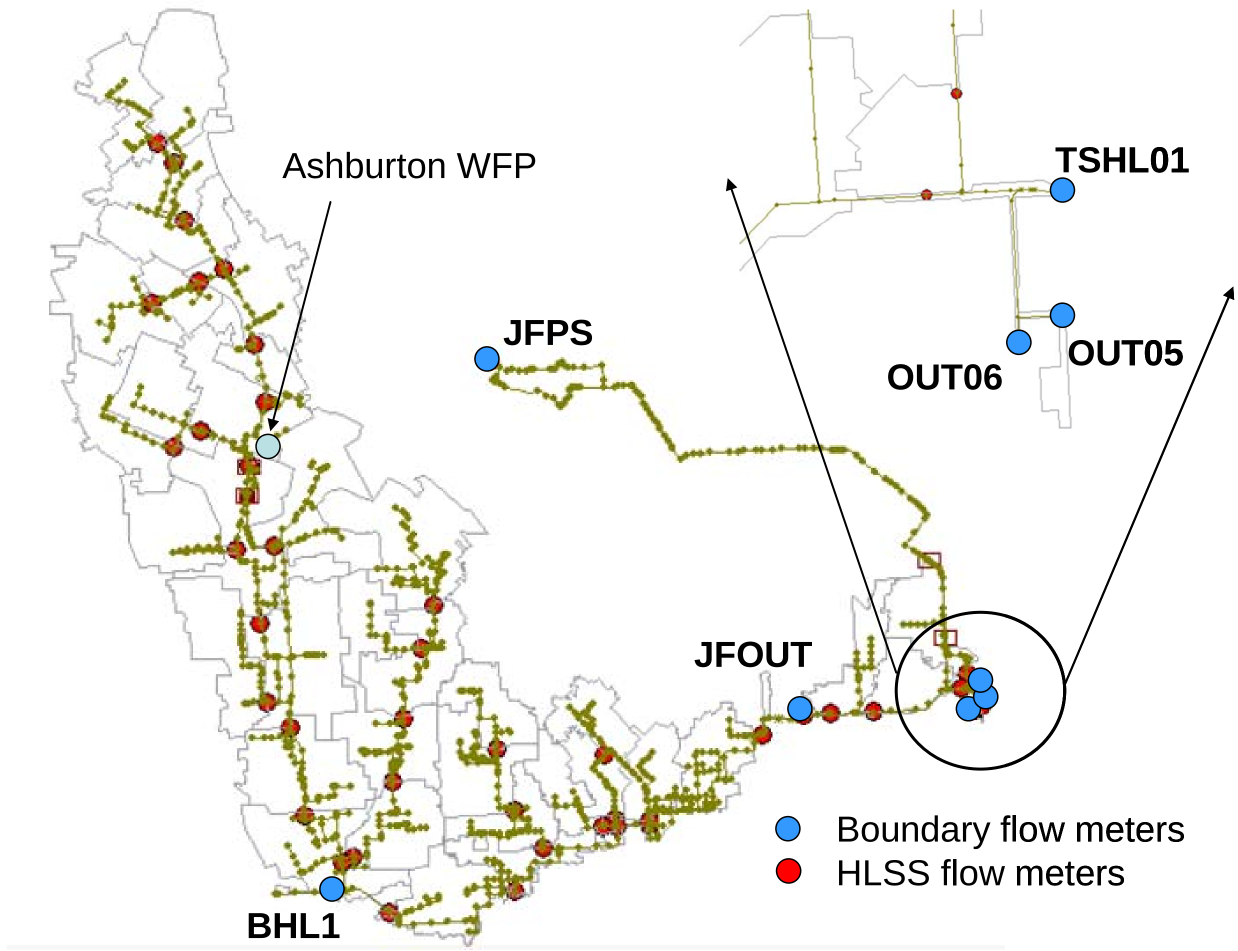


Figure 2-1. Location of HLSS boundary meters

Baltimore Street Diversion:

A portion of the flow from the Gwynns Falls sewershed was diverted by the City of Baltimore to HLI at the Baltimore Street Diversion (BSD). Historically this diversion was activated when the total flows to the Patapsco WWTP were excessive. The control valve to HLI, that was used to divert excessive flows to the Back River WWTP, has been closed since November 2007. However, several short periods of flow diversion are seen in the recent data during wet weather. The City is planning to minimize this wet weather flow into HLI, since it has capacity limitations and potential SSO problems near its downstream end. The flow from BSD was measured at the flow meter BHL1 (see Figure 2-1), and the flow rate ranged from 10 to 12.5 million gallons per day (MGD) during the recent monitoring period. The BSD flow rate exceeded 15 MGD three times during the primary flow monitoring period (May 2006 to May 2007) for HLSS drainage area.

Jones Falls Sewershed:

A portion of the flow from Jones Falls Sewershed is conveyed to the HLI through the Lower Jones Falls (LJF) Interceptor. The LJF interceptor is a 75" pipe that joins HLI at a location downstream of the inverted siphon that crosses the Jones Falls Express Way (I-83). Flow from this interceptor was measured by the flow meter JFOUT. The flow rate ranged, during dry weather periods, between 5 and 15 MGD, and increased to about 35 MGD during wet weather periods.

The 75" LJF Interceptor connects to the 66" HLI at approximately 21" below the HLI invert level at the junction point. Also, the downstream portion of LJF interceptor has experienced frequent surcharging and overflows due to flow back-up from the HLI. Therefore, the City has built a new relief pipe, called the Greenmount Interceptor, and connected to HLI approximately 1,200 feet east of the LBJ interceptor. The Greenmount Interceptor has been in service since May 2008. Since this is new construction, it will be included in the hydraulic analyses of the baseline and future rehabilitation scenarios, and not in the model calibration process that will essentially use the May 2006 to May 2007 data.

Jones Falls Force Main:

The Jones Falls Force Main (JFFM) carries flow from the remainder of the Jones Falls sewershed via the Jones Falls Pump Station. This conveyance system consists of 17,000 feet long 36" pressurized sewer (force main) section and a 4,000 feet long gravity section prior to joining the HLI. The gravity section includes a 36" existing sewer and a newly constructed 42" sewer line, SC-779, which has been in service since 2004. SC-779 was construction as part of other City Paragraph 8 projects (e.g., Jones Falls Pump Station upgrade project SC-822) to eliminate SSO No.5 which is an overflow weir at Jones Falls

Pump Station. The discharge from the pump station to HLI is 10 – 20 MGD for dry periods, however, the discharge increases up to 70 MGD for wet periods.

Eastern Avenue Pump Station:

The Eastern Avenue force main carries flow from the Eastern Avenue Pump Station. It is the largest boundary flow contributor to the HLI and this pump station collects flow from the entire Low Level Sewershed and sends it to the downstream end of HLI. The flow rate was measured at the meter OUT06 installed at the downstream end of the gravity section of Eastern Avenue force main. This discharge ranged from 10 to 40 MGD during dry days and peaked to about 80 MGD during wet weather periods. However, this 100" pipe had about 25" of sediment depth according to the flow metering location's site sheet, and the depth of flow during dry weather was between half to ¾ of pipe diameter. This high depth flow appears to create regular flow back-up in lateral sewers in the outfall sewershed, OUT05, as evidenced by the difficulty in obtaining any reliable flow monitoring data from this location.

Outfall Sewershed:

A smaller drainage area at the west end of Outfall sewershed contributes flow to the HLI through the large pipe that conveys flow from the Eastern Avenue Pump Station. The flow was measured at flow meter OUT05. As mentioned above, the gravity section of the Eastern Avenue force main creates surcharging conditions at this 15" lateral pipe on a daily basis. Therefore, the flow monitoring at this location was extremely difficult throughout the monitoring period due to high fluctuations in flows from the Eastern Avenue Pump Station

TSHL01:

The total flow from HLI and the other contributing sewersheds was monitored at a downstream location near the end of HLI, TSHL01. As shown in Table 2-1, total flow contributions from these incoming boundary flows constitutes a large portion of TSHL01 flow. The flow rate at TSHL01 provides inflow boundary conditions for the Outfall sewershed. The observed depth at TSHL01 provides hydraulic boundary conditions (specified as hydraulic gradient line, HGL) for HLSS that represents the ability of HLSS to send flows to the downstream Outfall Interceptor sewer towards the Back River WWTP.

Table 2-1. Dry and Wet Weather Flow Rate Range from HLSS Boundaries

Flow Sources	Flow Direction	Flow Meter	Pipe Size (in)	Dry weather flow range (MGD)	Peak wet weather flow (MGD)
Baltimore Street Diversion	Into HLI	BHL1	33"	10 - 12.5	18
Jones Falls Interceptor	Into HLI	JFOUT	78"	5 - 15	33
Jones Falls Pump Station*	Into HLI	JFPS	60"	10 - 20	66
Outfall Sewershed	Into HLI	OUT05*	15"	N/A	N/A
Eastern Avenue Pump Sation	Into HLI	OUT06	99"	10 - 40	76
HLSS and all the boundary flows	Out of HLI	TSHL01	144 (W) * 129 (H)	70 - 90	170

* Flow meter is located near pump station, upstream of Jones Falls Force Main
* OUT05 didn't work properly due to high flow fluctuation from Eastern Avenue Pump Station

2.3 MODEL EXTENT

In accordance with the specifications in the consent decree (CD), the HLSS system micro-model included all the gravity and pressure sewers listed below:

- all sanitary sewers 10-inch and larger in diameter;
- all 8-inch sewers necessary to accurately represent the hydraulic connectivity, where needed;
- all sewers connecting the pump station service areas; and
- all sewers that have historically contributed to capacity-related overflows and engineered SSO locations which were designed to alleviate localized surcharging/flooding until the rehabilitation projects under Paragraph 8 were completed.

The HLSS team reviewed historical overflow records and data from the Paragraph 8 SSO monitoring program to determine the necessary modeling extent that will comply with the CD requirements

The engineered SSOs that were active during the primary flow monitoring period were included in the model extent. For historical SSOs, the 2003 – 2008 SSO records were carefully reviewed to select all the capacity related SSOs and the appropriate sewer sections were included in the model.

There are no permanent pump stations located within the HLSS area. It should be noted, however, that there are temporary pumping stations in the Washwater Lake which currently discharges backwash water from Ashburton WFP to 18" existing Gwynns Run Interceptor (GRI). The GRI has experienced frequent overflows due to flow overload, however, is now being relieved by the 30" relief line, SC-812, that runs parallel to the GRI. The total discharge from this pump station can be up to 10 MGD, and its discharge was included in the model as time-series inflow at an appropriate manhole. The Washwater Lake has been under rehabilitation (WC-1143), and these pump stations will be taken out of service once the lake rehabilitation and gravity drain are completed.

THIS PAGE INTENTIONALLY LEFT BLANK

SECTION 3 – MODELING TOOL AND MODELING PROCEDURE

3.1 MODELING TOOL – INFOWORKS CS

There are a number of public or commercial hydraulic modeling software that are suitable for sewershed studies. The City had undergone a modeling software evaluation and selection process and presented the top three candidate software – InfoWorks CS, MOUSE, and XPSWMM in the "Wastewater Collection System Model Project Approach Report". These were submitted to the USEPA, MDE and the Department of Justice (DOJ). The City subsequently selected InfoWorks CS, developed by the Wallingford Software, as uniform platform to be used for the city-wide sewershed studies.

InfoWorks CS is among the leading commercial software available for I/I analysis and sewer system rehabilitation planning. It has a dynamic rainfall-runoff simulation module that can be used for single event and/or long-term (continuous) simulation of runoff quantity and quality from primarily urban areas. Although the HLSS is a separate sanitary system that should not receive any direct runoff from the streets/catchbasins, the inflow and infiltration that occur during wet weather events can be characterized using the runoff module in InfoWorks.

The model seamlessly integrates the rainfall-runoff module simulating the hydrology with a hydraulic module that simulates flow through the conduit networks (pipes, channels, etc.) and flow-control elements (sluice gates, pumps, storage/treatment devices, etc.). Once the specifics of a drainage area and its sewer system network are inputted into the program, InfoWorks CS computes flow rate and water depth in each modeled conduit (pipe) during each time step of the simulation period.

The model outputs can be viewed in a variety of graphical and/or tabular formats. Hydrologic and hydraulic data in GIS format can be imported directly to develop certain input parameters or for visualization purposes. The model solves the complete Saint Venant's (dynamic flow) equations for hydraulic calculations. It can characterize the backwater effects, flow reversal, surcharging, looped connections, and pressure flow in sewer systems. Figure 3-1 shows the visual user interface that includes a GIS-like menu on the left panel to select specific model attributes that one wants to visualize and a visualization panel on the right that shows these attributes in a plan or cross-sectional view.

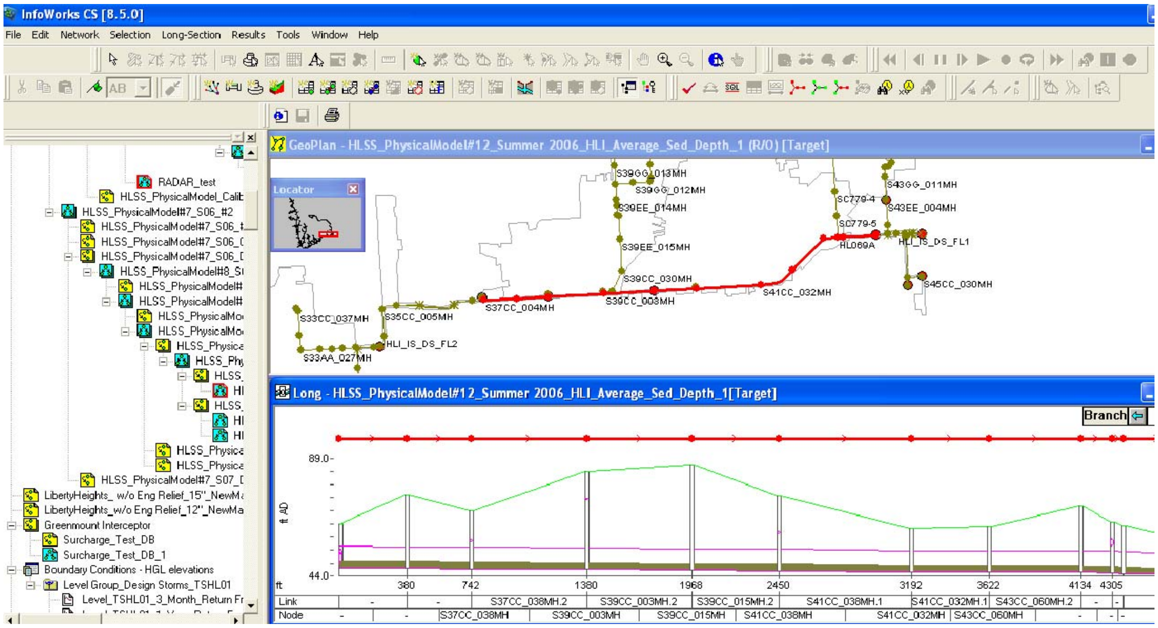


Figure 3-1. InfoWorks CS User Interface

3.2 MODEL FRAMEWORK

As briefly described in 3.1, sewer system models including InfoWorks CS have two simulation modules: the rainfall-runoff generator (to simulate Rainfall Dependent Inflow and Infiltration, i.e., RDII for sanitary systems), and hydraulic module that routes flow through the sewer system and control elements. These two modules are briefly described in the following two sections.

3.2.1 Hydrology Calculation

In accordance with the BaSES manual guidelines, the SWMM RUNOFF hydrology calculation module of InfoWorks CS was used to simulate the wet weather flow responses (i.e., RDII) for the HLSS. It simulates a drainage basin as a collection of subcatchments, each representing idealized runoff-producing areas with uniform physical characteristics such as surface roughness, percent imperviousness, and ground slope. Detailed meteorological data and surface characteristics are required as model input to generate runoff hydrographs for each subcatchment. The model uses this information to generate continuous rainfall driven wet weather inflow that can reach specific nodes (manholes) representing inlet points for the HLSS collection system.

The RUNOFF module conceptualizes each subcatchment as a non-linear reservoir (Figure 3-2), with an initial abstraction induced by surface depressions (also known as depression storage). The applied rainfall is subsequently reduced by infiltration and evaporation. The remaining volume is then used to calculate the subcatchment outflow.

Manning's equation, in the following form, is used by the model to calculate outflow from each subcatchment area:

$$Q = W \frac{1.49}{n} \left(d - d_p\right)^{5/3} S^{1/2}$$

where:

Q	=	subcatchment runoff (cubic feet per second [cfs]),
W	=	subcatchment width or width of overland flow (ft),
n	=	Manning's roughness coefficient,
d	=	water depth of rainfall and snowmelt (ft),
dp	=	depression storage depth (ft), and
S	=	land slope (ft/ft).

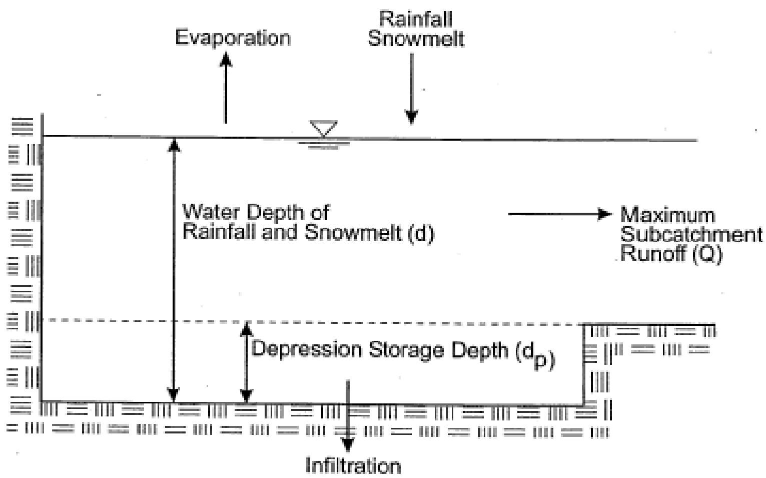


Figure 3-2. Non-linear Reservoir Conceptualization

The RUNOFF module was originally designed to calculate runoff from storm sewer or combined sewer drainage areas, by allowing users to specify the surface characteristics of each subcatchment that are required to calculate and route the entire runoff flow. The characteristic parameters include drainage area, percent imperviousness, land slope, width of overland flow, and Manning's surface roughness coefficients. Additionally users can input hydrology parameters of a study area such as infiltration rate, evaporation, and depression storage. These parameters are used to calculate the volume and velocity of the generated overland flow that eventually enters a sewer system.

Unlike the hydrology calculations for the combined/storm sewers, majority of the RUNOFF parameters no longer bear their real physical meaning for sanitary sewer systems. The immediate inflow into a sewer system can result from several field conditions including connection of roof leaders from homes to a sanitary sewer or improper connection of a storm catch-basin to a sanitary sewer. A slightly delayed inflow can result from leaky or low-lying manholes that have the potential to drain some runoff from streets or nearby streams into a sanitary sewer. A much extended inflow can result from damaged pipes (cracks in joints or structural collapses, for example) that can receive additional flow when the groundwater levels rise or during a temporary water main break. The US EPA has recently supported a cooperative research project (SSOAP) that outlines a triple-unit-hydrograph methodology to characterize the immediate, slightly delayed, and extended flow patterns into sanitary sewers. Several methodologies can be used to characterize these three unique inflow patterns, and the methodology to be utilized in this project uses a Directly Connected Impervious Area (DCIA) concept. A fraction of the contributing drainage area with 100% imperviousness is assumed to contribute, for example, the immediate inflow into sewers. The DCIA fraction can be fully or partly supported by an understanding of field conditions. If we know that every other household's roof leader is inadvertently connected to sanitary sewers, based on field surveys, then half of the total roof surfaces in the contributing area can be used as the starting DCIA value. It can then be used as a calibration parameter in order to obtain good correlation between the monitored and modeled inflows. A similar exercise can be carried out for the slightly delayed and much extended inflow patterns. The typical RUNOFF parameters fine-tuned to represent the duration and peaking, namely, the overland flow width and surface roughness coefficient can be adjusted to accurately reproduce the three distinct inflow patterns.

The volume and peak flow of the RDII are determined largely by the age and condition of the sewers, prevalence of illegal connections, and soil moisture conditions. However, the RUNOFF module can work as a generator resulting in continuous RDII derived from the variable rainfall conditions. Some of the parameters such as the initial loss value (depression storage), and the RDII capture coefficient (fraction of rainfall that gets translated to RDII volume in the sewers) can be conceptualized and derived from a regression analysis of the measured RDII data with respect to rainfall. The models will then be calibrated to get good correlation between the monitored RDII volume and peak flow to their modeled values. The details of the methodology and its application in model calibration are discussed in Sections 4 to 6.

3.2.2 Hydraulic Calculations

InfoWorks CS solves the complete St. Venant dynamic flow equations for routing within a sewer system and control devices such as pumps and sluice gates. The model uses hydrologic and sanitary flow inputs to perform dynamic routing of flows in sanitary sewers and through the interceptor sewers. Backwater, surcharging, and other conditions influence system responses and identify potential SSOs along the sewer system. The simulation output provides time-varying water surface elevations and flow rates at selected locations. For hydraulic calculations the governing factors are the connectivity of the sewer network, accuracy of the sewer size and profiles, sediment conditions and sewer roughness, as well as the system operation and maintenance aspects. In addition, how the various flow components (sanitary, ground water infiltration, industrial and commercial discharges, RDII, etc.) are distributed throughout the sewer system are also critical for getting the correct flow predictions.

3.3 MODELING PROCEDURE

3.3.1 General Modeling Procedure

Several steps are involved in the modeling process of a sewershed, including data acquisition and assessment, model network construction and model input development, model calibration and validation, and model application. Each of these steps is described in the following sub-sections.

3.3.1.1 Data Acquisition and Assessment

Data acquisition is a critical step in the development of a hydraulic model. In this step, the data pertaining to a study area is obtained from various available sources either to characterize the sewershed for constructing a model network and developing model parameter values, or to provide a basis for evaluating the model performances.

In order to build a model network, physical information of structures in a sewer system (manholes, pipes, diversion chambers, weirs, gates, pump stations, etc.) are necessary. Nowadays, digitized pipe network databases in GIS compatible format have become largely available for a large number of municipalities in the U.S. Additional information including paper drawings, field inspection reports, and operational records are used to supplement and improve the existing digital databases. New technologies like CCTV survey can provide up-to-date information on structural damages or obstructions in the pipes.

For computing wet weather flow generation from each drainage area, characteristic data such as drainage area size, land use and land cover, percent imperviousness, ground contours, and soil types need to be obtained. Also needed are the meteorological and hydrological data such as rainfall, evaporation, infiltration rate, and depression storage.

Historical hydraulic data (flow, water level, and velocity) are necessary for model calibration and validation to ensure that the model can well represent the sewer system bottlenecks or surcharging observed in the field. For sanitary sewer systems, historical SSO occurrence records and sewer backup/basement flooding complaint data can be very useful for evaluating how the model simulates the events in the past.

Any monitored data must undergo a thorough review and quality control before they can be used in the model. Data in good quality and quantity reduces the model uncertainty and enhances robustness of the model in representing the real-world hydraulic conditions.

Various statistic tools and procedures can be used to perform the data quality check, and this process is often integrated with the process of data analysis for developing model inputs. The details of data acquisition and analysis pertinent to the HLSS study are discussed in Section 4.

3.3.1.2 Model Network Construction and Model Input Development

Model network construction begins with setting up the nodes (manholes) and links (e.g., pipes, force mains, and pump stations) that simulate the real-world physical pipe network connectivity. In the next step, the drainage area must be segmented to subcatchments as smaller hydrology calculation units. Subsequently, initial values of parameters for pipe network and drainage subcatchments need to be populated based on data compiled thus far.

In a sanitary sewer system, the total flow consists of several components (as illustrated in Figure 3-3): base ground water infiltration, waste water production including sanitary flow from residential areas and waste flow from industrial dischargers, and RDII flow during wet weather periods. Except for the RDII flows, the quantity and time variation patterns of each flow component need to be developed for each contributing drainage area and distributed throughout the model network based on their connection points to the sanitary sewer system. The model's wet weather flow generator is adopted to calculate RDII for the given rainfall data and subcatchment parameters. Boundary conditions, such as inflows from connecting sewersheds, WWTP plant headwork, or tidal influences at outfalls, need to be compiled and provided as an external time-series input into the model.

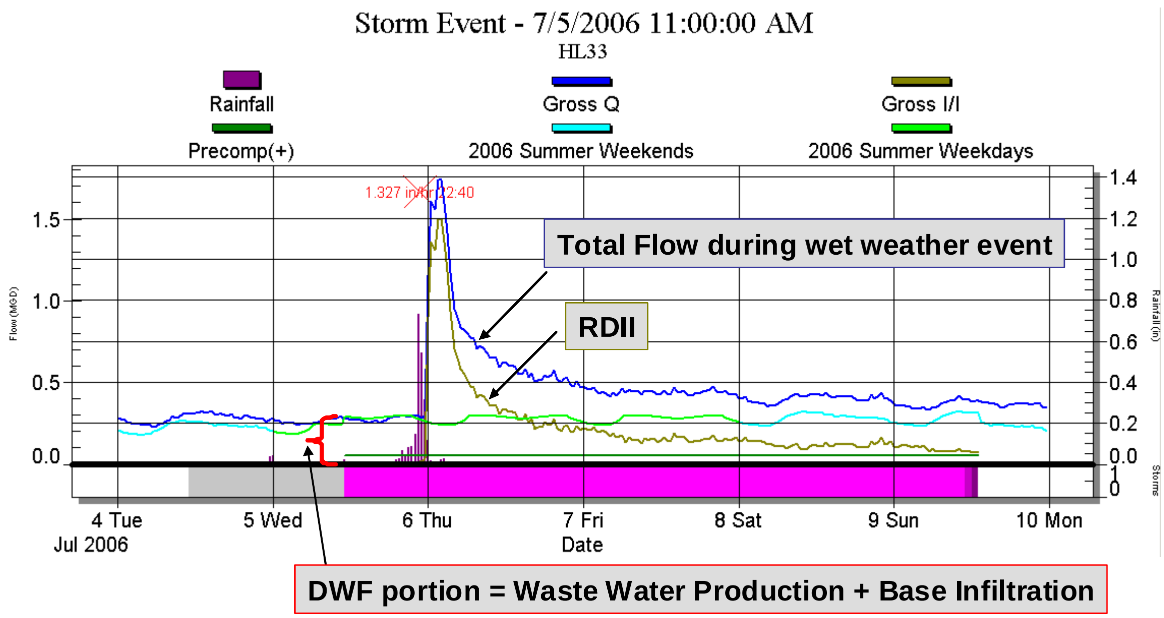


Figure 3-3. Flow Components in Sanitary Sewer System

The details of model construction and input development process for the HLSS system are described in Section 5 of this report.

3.3.1.3 Model Calibration/Validation and Result Evaluation

Subsequent to construction, the model needs to be calibrated and validated using historical data. This process consists of two steps: dry weather calibration and wet weather calibration.

Dry weather calibration ensures that the model representation of the dry weather flow components (base infiltration and waste water production, along with any significant dischargers) is accurate, before the more complex RDII is introduced during wet weather. This process is conducted based on selected time-periods in the historical flow monitoring with several continuous dry days with no influence from the antecedent soil moisture. By checking the flow, water depth and velocity at a number of locations in the sewer system, the quantity, time variation and allocation of the dry flow components can be appropriately defined from the various contributing drainage areas and refined, if needed. Following this process, the wet weather calibration focuses on simulation of RDII reaching the sanitary sewers.

In order to enhance the robustness of model performance, wet weather calibrations are conducted based on a variety of rainfall events with different patterns in terms of the event volume, intensity and duration. Appropriate calibration parameters are adjusted to optimize the matching of modeled and monitored data for wet weather volume, peaking and the time-to-peak for the hydrographs at all or most of the metering locations. Statistical tools are also used to the overall adequacy of model calibration.

When the model calibration is completed, the same parameters are used in simulating a few independent dry and wet weather events. This constitutes a model validation process, which is used to confirm that the model can be used for conditions different from those used for model calibration. Model validation, in essence, enhances the model robustness for application to future conditions including capacity analyses using the design storms. Section 6 of this report discusses the HLSS model calibration and validation process and the methods used to evaluate modeling results.

3.3.1.4 Model Application

Using the appropriate model calibration and validation processes, the models become good tools to forecast what may happen under future climatic conditions or with physical changes to a sewer system. Consequently they become very critical in assisting decision-makers in evaluating a range of options and selecting the most appropriate and cost-effective solution in a sewer rehabilitation process.

Upon verification of the micro model by 1015, the calibrated model will be used to characterize the collection system under baseline and future conditions for a variety of design storms from 3-month to 20-year severity. For the future condition, the model will be altered to take into account conditions as they will be in the year 2020. Once the future conditions have been established, the model will be used to evaluate alternatives to mitigate SSOs in the City.

3.3.2 BaSES Guidance for Baltimore Projects

The City has compiled a Baltimore Sewer Evaluation Standards Manual (BaSES) in accordance with the CD requirements in order to provide guidelines to the eight consultants for citywide sewershed and collection system studies. Hydraulic modeling protocols are described in Section 7 of the BaSES manual, and the general modeling procedure discussed in the above sections are consistent with the BaSES guidelines. The BaSES has also specified detailed approaches for the following modeling tasks that should be adopted by the individual sewershed consultant teams.

- Modeling Phases
- Model Software
- InfoWork CS Data Requirement
- Model Network Extent and Basin Representation
- Dry and Wet Weather Flow Development
- Model Calibration Criteria and Method for Result Evaluation

- Baseline Assessment, Capacity Analysis and Alternatives Evaluation
- Report Requirements
-

The HLSS team adopted the BaSES guidelines throughout the modeling process, and supplemented with the expertise and tools developed in similar previous projects conducted by the various team members. Details of the modeling approaches are discussed in Sections 4 to 6.

THIS PAGE INTENTIONALLY LEFT BLANK

SECTION 4 – DATA SOURCES AND ANALYSIS TO SUPPORT HYDRAULIC MODEL DEVELOPMENT

4.1 DATA SOURCES

The City has several data sources available from the previous sewer system characterization efforts. Similarly, a range of field activities has been performed as part of the HLSS study including field surveys and inspections. The HLSS modeling team reviewed all of the sources and used most of them to support the sewer system characterization. These datasets are described in the following sections.

4.1.1 Flow Monitoring

The objective of flow monitoring programs is to quantify the flow conditions in sewers during both dry and wet weather conditions. Flow data is used to support the model calibration and to assess the localized bottlenecks or hydraulic conditions.

Monitoring of flow, depth and velocity was conducted in HLSS during several time periods. City-wide flow monitoring, conducted by three flow monitoring contractors, provided an extended monitoring record for HLSS and the other sewersheds. In addition, short-term monitoring was conducted to support localized hydraulic analyses. These monitoring programs are discussed in detail below.

Flow monitoring data can be visualized and processed by Sli/icer.com, a web-based software developed by ADS Environmental Services. Sli/icer.com (Sli/icer) was selected as the official flow data management and processing software by the City, and all the sewershed teams are using it for the Inflow and Infiltration Evaluation tasks. Details of the functionalities in Sli/icer pertinent to the dry and wet weather flow analyses are further described in Section 4.3.1. Table 4-1 summarizes the flow meter installation history for all the HLSS flow meters.

City-wide Monitoring

Flow monitoring was conducted in HLSS at 45 locations including five boundary flow meters (map shown in Figure 4-1). These locations were selected by the City so that every flow meter basin contained comparable lengths of sanitary pipes. The primary monitoring period for HLSS extended from May 2006 to May 2007, which captured 29 storm events greater than 0.5” in total rainfall volume and sufficiently widespread to affect the entire system. The locations BHL1, JFPS, JFOUT, OUT05 and OUT06 are boundary meters that provided information on total flows contributed by surrounding sewersheds into HLSS. Similarly, TSHL01, TSHL03, HL08A and HL09A are the locations used for macro model calibration by the City’s technical management team,

1015. As shown in Figure 4-1, there are 11 meters including 4 boundary meters that are continuously being operated by the City for long term flow monitoring.

For each flow meter, a one-page site sheet was provided by the corresponding flow metering contractor. Figure 4-2 shows the site sheet for HL38 as an example. A site sheet provides information on the flow meter location, manhole/pipe structure, hydraulic data, and any miscellaneous information such as inspection date and the inspector's name. The location information includes vicinity maps, photos, manhole identification number, and the global positioning system (GPS) coordinates. Structural information includes the manhole depth, width, and material as well as the pipe size, material, and invert depth of all incoming and outgoing pipes Hydraulic information includes installation photo, flow depth and velocity measured during the inspection, and silt level. These manual depth and velocity confirmation measurement are used to both to set up the flow meter and to provide useful insights to help resolve conflicts between meter and modeling data.

SC812 Relief Pipe

The City has constructed temporary and permanent relief pipes to alleviate overflow conditions in HLSS. One such relief is the SC812 project constructed near the Ashburton Water Filtration Plant. The new relief line was constructed to alleviate frequent overflows that occur near 2800 Dukeland Street and was put into service in February 2007. It is a 30" relief line that diverts all the upstream GRI flow from HL31 to the GRI downstream of HL25. The existing line, which varies in pipe size from 18" to 32", runs parallel to the SC812 relief pipe, collecting local flows (e.g., HL25, HL26, HL28, etc.) and conveying discharges from the Washwater Lake. In order to evaluate the effectiveness of the newly constructed SC812 relief, four new flow meters were installed at the upstream and downstream ends of SC812 and the relieved portion of GRI. Figure 4-3 shows the schematic of these four flow metering locations. These meters were installed on April 8, 2008 and are still in operation as of November 2008.

Siphon at High-Level Interceptor

A triple-barrel siphon exists in the HLI where Eager Street crosses the Jones Falls Expressway (I-83). This siphon had experienced frequent surcharging, resulting in some overflows, at both the upstream and downstream ends. These SSO events could result from capacity limitations either in the siphon or somewhere further downstream of HLI. In order to study the hydraulic conditions in the siphon (i.e., capacity and head loss) and to determine if the siphon has any capacity limitations, two new flow meters (HLS1 and HLS2) were installed at the upstream and downstream ends of the siphon. These meters were installed on June 19, 2008, and are still in operation as of November 2008. Figure 4-4 shows the flow metering locations with an aerial photograph as background.

Table 4-1. HLSS flow meter installation history

Flow Meter	Installation Purpose	Installation Date	Removal Date*
HL41	I/I	5/9/2006	2/29/2008
HL40	I/I	5/9/2006	2/29/2008
HL39	I/I	5/9/2006	2/29/2008
HL38	I/I	5/9/2006	2/29/2008
HL37	I/I	5/9/2006	2/29/2008
HL36	I/I	5/9/2006	2/29/2008
HL35	I/I	5/9/2006	Long Term Meter
HL34	I/I	5/9/2006	2/29/2008
HL33	I/I	5/9/2006	Long Term Meter
HL32	I/I	5/9/2006	Long Term Meter
HL31	I/I	5/9/2006	Long Term Meter
HL30	I/I	5/9/2006	5/18/2007
HL29	I/I	5/9/2006	5/18/2007
HL28	I/I	5/9/2006	5/18/2007
HL27	I/I	5/9/2006	5/18/2007
HL26	I/I	5/9/2006	5/18/2007
HL25	I/I	5/9/2006	5/18/2007
HL24	I/I	5/9/2006	5/18/2007
HL23	I/I	5/9/2006	5/18/2007
HL22	I/I	5/9/2006	5/18/2007
HL21	I/I	5/9/2006	5/18/2007
HL20	I/I	5/9/2006	Long Term Meter
TSHL03	Calibration Meter	5/9/2006	Long Term Meter
HL19	I/I	5/9/2006	5/18/2007
HL18	I/I	5/9/2006	5/18/2007
HL17	I/I	5/9/2006	5/18/2007
HL16	I/I	5/9/2006	5/18/2007
HL15	I/I	5/9/2006	5/18/2007
HL14	I/I	5/9/2006	5/18/2007
HL13	I/I	5/9/2006	5/18/2007
HL12	I/I	5/9/2006	5/18/2007
HL11	I/I	5/9/2006	5/18/2007
HL10	I/I	5/9/2006	5/18/2007
HL09A	Calibration Meter	5/9/2006	5/18/2007
HL09	I/I	5/9/2006	Long Term Meter
HL08A	Calibration Meter	5/9/2006	5/18/2007
HL08	I/I	5/9/2006	5/18/2007
HL07	I/I	5/9/2006	5/18/2007
HL06	I/I	5/9/2006	5/18/2007
TSHL01	Calibration Meter	5/9/2006	Long Term Meter
BHL1	Boundary Meter	5/9/2006	Long Term Meter
JFPS	Boundary Meter	5/9/2006	Long Term Meter
JFOUT	Boundary Meter	5/9/2006	5/18/2007
OUT05	Boundary Meter	5/9/2006	5/18/2007
OUT06	Boundary Meter	5/9/2006	Long Term Meter
* Removal date as of February 2008			

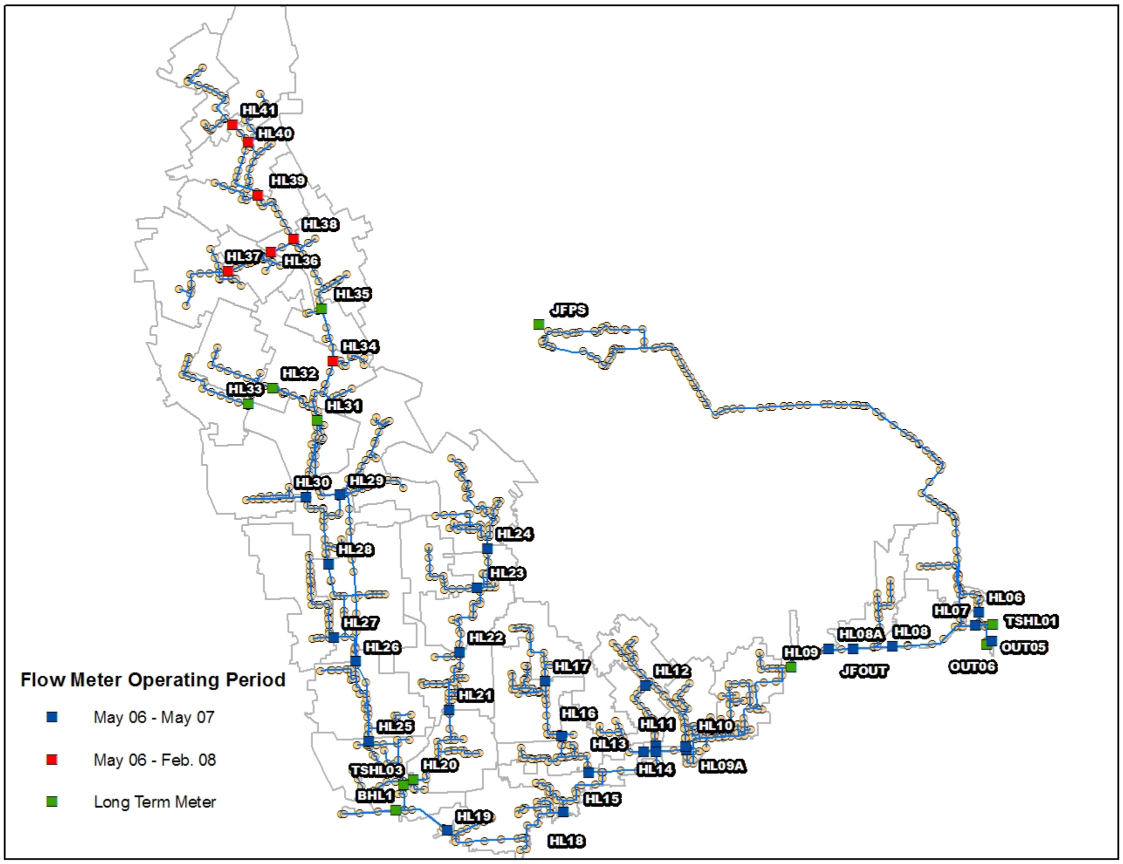


Figure 4-1. Period of system-wide flow monitoring in HLSS

ADS ENVIRONMENTAL SERVICES	City of Baltimore - Bureau of Water and Wastewater Flow Monitoring Services for Sanitary Sewer System	Site Name HL38

Sewershed	Project No.	Inspection Date/Time	City MH I.D.			
High Level	995S	1/17/06 - 16:25	S11GG1011MH			
		Inspected By	Manhole		Pipe	
		DER, WK	Depth (ft)	Width (ft)	Width (in)	Height (in)
Site Address:	#4221 Towanda Ave.		9.9	4'00"	14.00	

MH Type: ☑ Brick ☐ Precast | Pipe Type: ☐ Brick ☐ Concrete ☐ Clay ☐ Metal ☑ Other | Pipe Shape: ☑ Circular ☐ Box ☐ Odd

PART A - SITE INVESTIGATION

Top View Picture

Area Location Map

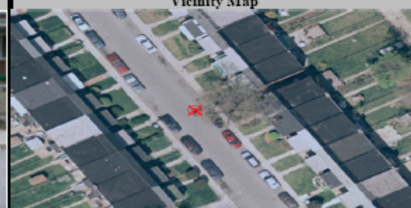
Safety Concerns
☐ Gas ☑ Traffic
☐ Access ☐ Other
☐ None

Meter Location
☑ U/S
☐ D/S

Manhole Coordinates
X 1406417.66
Y 608269.82

Area View Picture

Vicinity Map



Telog Antenna Installation
☑ Asphalt ☐ Soil
☐ Concrete ☐ Traffic
☐ Other

System Characteristics
☑ Residential
☐ Commercial
☐ Industrial

Hydraulic Assessment

Surcharge (ft): 0 | ☑ Straight | ☐ Bend | ☐ Drop Inlet | ☐ Backwater | ☐ Pump Sta. | ☐ WWTP | ☐ Needs Cleaning

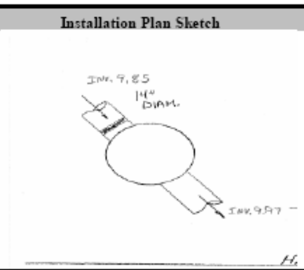
Flow Depth (in): 5 | Instant. Vel (fps): 3.5 | Silt Level (in): 0 | Signs of I/I: None

HYDRAULIC RATING: ☑ A (good) ☐ B (questionable) ☐ C (poor) | Recommended for Installation ☑ Yes ☐ No

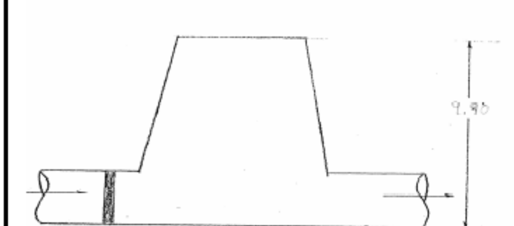
COMMENTS: | Meter Type: Isco Ultra PV

PART B - SITE INSTALLATION

Installation Plan Sketch



Installation Profile Sketch



Installation Information

	Incoming				Outgoing	OF
Line #	1	2	3	4	1	1
Size (in)	14				14	
Material	Lined				Lined	
Debris (Y/N)	N				N	
Shape	Cir				Cir	
Flow Depth (in):	5				5	
Instant. Vel. (fps)	3.5				3.5	
Invert Elevation (ft)	9.85				9.97	

Comments:

Installation Photo

Figure 4-2. Flow metering site sheet for HL38

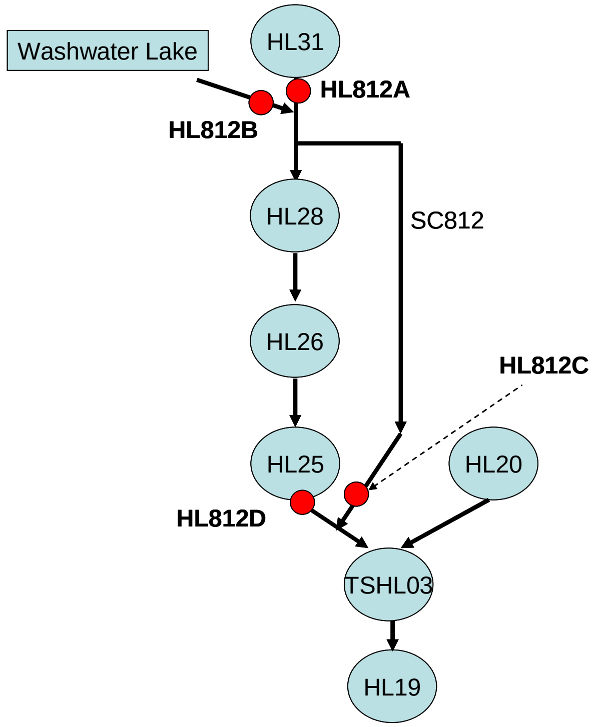


Figure 4-3. New Flow Meters for the SC812 Relief Line

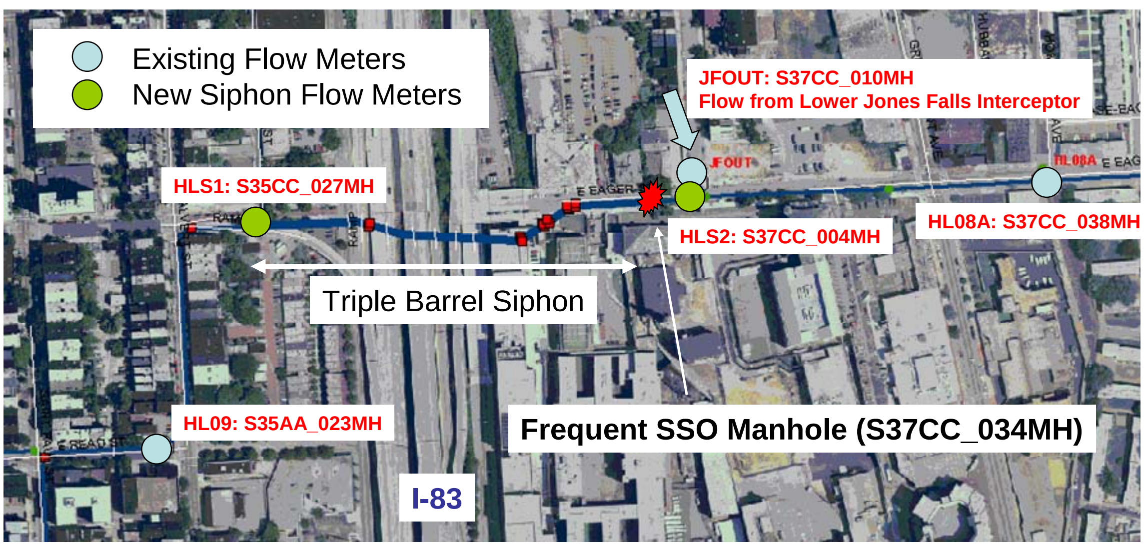


Figure 4-4. New Flow Meters on both ends of the HLI Siphon

4.1.2 Historical SSO Records

Historical SSO records are among the most important datasets for supporting the hydraulic model development and calibration. The ultimate goal for the city-wide sewer rehabilitation program is SSO elimination. Simulation of historical SSOs provides the greatest confidence in model calibration and also paves the way for assessing future rehabilitation efforts using this hydraulic model. During model development, the network was extended to include 8" pipes in order to simulate all the major capacity-related SSOs. During the validation process, the modeling team reviewed the model to ensure that the simulated flows were close to observed values at the metering locations and also to confirm that the recorded SSO events were appropriately reproduced at the frequent SSO locations for major storms.

This section summarizes two different SSO datasets made available by the City of Baltimore and their use in supporting the hydraulic modeling tasks. Also included is a brief description of the SSOs that frequently occur in front of the Baltimore City Detention Center.

CSO/SSO Notifications:

The City has maintained an up-to-date CSO/SSO notification table on its website, which contains CSO and SSO records compiled on a monthly basis and summarized in the quarterly reports submitted to the US EPA and MDE. The CSO/SSO notification table is located at:

http://www.baltimorecity.gov/government/dpw/water/ConsentDecree/cso_ssoNotifications.php

This monthly table contains the following data entries:

- Serial No.
- Date of Occurrence
- Location
- Zip Code
- Reason
- Stream Affected
- Duration (hours)
- Time
- Description of Discharge
- Estimation of Quantity of Discharge (gallons)
- Measures Taken to Minimize Discharge
- Preventive Action to Stop Recurrences
- Work Order No.

The modeling team used this information to select only the significant historical SSOs in HLSS for inclusion in the model and associated analyses. Based on the location and zip code, the SSO points were imported to GIS for visualization. The information contained in “Reason/Measures/Preventive actions” was used by the modeling team to judge whether the SSO was due to a temporary sewer blockage (i.e., roots, rags, and grease buildup). This category of SSOs can be eliminated if effective preventive measures such as jet cleaning are undertaken. Only SSOs that were capacity related and recurred frequently at the same location, were selected for further analyses. The estimated discharge quantity indicated the magnitude of an overflow event.

All 514 CSO/SSO notification records available for the period of January 2003 to June 2008 were reviewed to determine the capacity-related overflow events in HLSS. From these records, five critical SSO locations which experienced a total of 20 SSOs were chosen. Figure 4-5 shows these five SSO locations, and Table 4-2 includes all SSO records for these locations. All five locations are along or close to the GRI. It should be noted that some of these SSOs may have been alleviated by the new relief pipe constructed under the SC812 project.

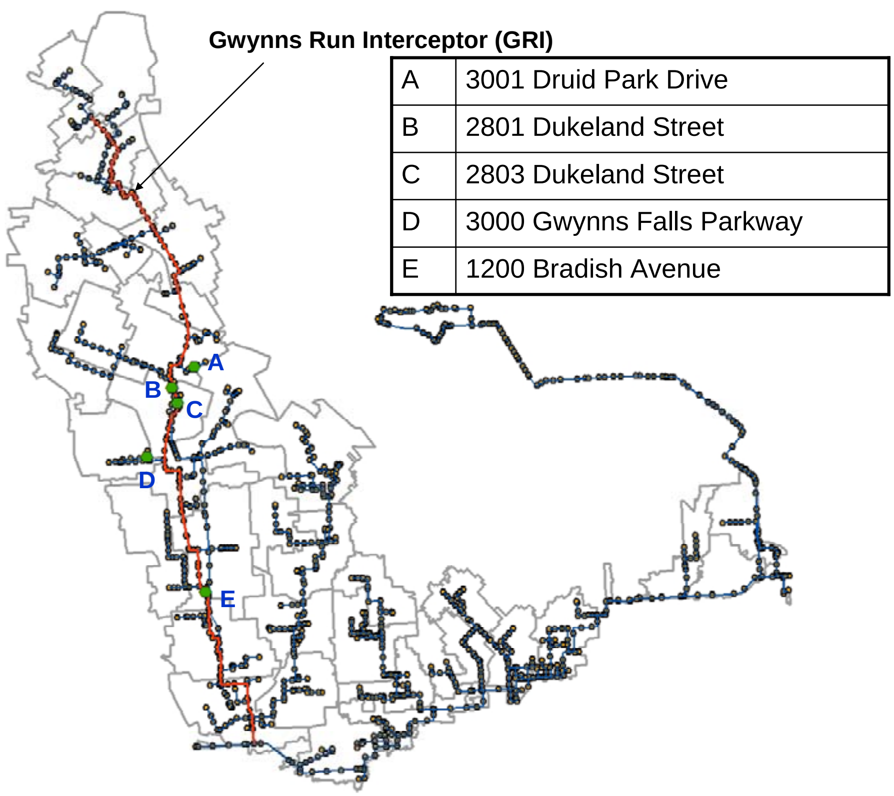


Figure 4-5. Recurring and capacity-related SSO locations in HLSS

Table 4-2. Capacity-Related SSO Records in HLSS

Place ID	Date of Occurrence	Location	Reason	Stream affected	Duration (hr)	Time	Description of Discharge	Estimated Quantity (gal)	Measures Taken to Minimize Discharge	Preventive Actions to Stop Recurrences	REMARKS
A	10/29/2003	3001 Druid Park Drive	Overcharged lines	Jones Falls	1	9:00-9:30	Raw sewage	450	None	Line will be monitored and placed on a preventive maintenance regime if necessary	No action was taken due to heavy rainfall
B	7/7/2006	2801 Dukeland Street	Structure:Sewer Manhole. Rags, Board	Gwynns Falls	7	7:00AM to 2:00 PM Stopped	N/A	100	18" Inch Sun Main Line Bulkland	off mil by Pass Pump	Estimated Quantity: 100 GAL Per Min TOTAL 2000, Duration: 7:AM to 2:00 PM Stopped
B	11/8/2006	2801 Dukeland Street	Structure:Sewer Manhole. Heavy Rain, Infilt/Inflo	Gwynns Falls	1	11/08/06 9:15A.M. - 11/8/06 9:56A.M.	Heavy Gray Water	123000	Line Receded on ITS OWP	Follow up Inspection of the San Maid line	SR# 44162, Duration : 11/08/06 9:15A.M. -11/8/06 9:56A.M.
C	5/20/2005	2803 Dukeland Street	Heavy Rain,Infiltr and Inflo,Main blckd by debris	Gwynns Falls	12	8:00 A.M. - 7:30 P.M	Heavy gray colored water.	690000	Relieved using bypass pumping	Set up pump to by pass flow to clean the debris in line and conduct repair work.	SR # 10759, Reason: Heavy Rain, Infiltration and Inflow, Also Sewer Main blocked due to debris in line
C	5/24/2005	2803 Dukeland Street	Heavy Rain,Outlet pipe broke at Mnhole,Main blckd	Gwynns Falls	4	5:00 A.M.- 8:45 A.M.	Heavy gray colored water.	107850	Relieved using 8" pump to bypass the flow.	Set up pump to by pass flow to clean the debris in line and conduct repair work.	SR # 10938, Reason: Heavy Rain, Outlet pipe broke at the Man hole, Sewer Main blocked due to debris in line.
C	5/24/2005	2803 Dukeland Street	Heavy Rain,Outlet pipe broke at Mnhole,Main blckd	Gwynns Falls	4	5:00 P.M. - 9:00 P.M.	Heavy gray colored water.	3600	Relieved using bypass pumping	Set up pump to by pass flow to clean the debris in line and conduct repair work.	SR # 10938, Reason: Heavy Rain, Outlet pipe broke at the Man hole, Sewer Main blocked due to debris in line.
C	5/25/2005	2803 Dukeland Street	Broken Outlet Pipe @ M.H. under repair,Main blckd	Gwynns Falls	10	5:30 A.M. - 3:00 P.M.	Heavy Gray colored water.	22800	Relieved using bypass pumping	Set up pump to by pass flow to clean the debris in line. Repair of M.H. Outlet pipe & line cleaning operation under way	SR # 10986 , Reason: Broken Outlet Pipe @ M.H. under repair / Sewer Main blocked due to debris in the line.
C	5/29/2005	2803 Dukeland Street	Main surchrged & blckd, Outlet pipe @M.H.being fix	Gwynns Falls	8	6:00 A.M. - 2:00 P.M.	Gray colored water	48000	Relieved using bypass pumping	Set up pump to by pass flow to clean the debris in line. Repair of M.H. Outlet pipe & line cleaning operation under way	SR # 10938, Reason: Sewer Main surcharged & blocked due to debris in line / Broken Outlet pipe @M.H.under repair
C	5/30/2005	2803 Dukeland Street	Main surchrged & blckd, Outlet pipe @M.H.being fix	Gwynns Falls	9	10:30 A.M (5-30-05). - 1:30 A.M. (5-31-05)	Gray colored water	45000	Relieved using bypass pumping	Set up pump to by pass flow to clean the debris in line. Repair of M.H. Outlet pipe & line cleaning operation under way	SR # 10986 , Reason: Sewer Main surcharged & blocked due to debris in line / Broken Outlet pipe @M.H.under repair
C	5/31/2005	2803 Dukeland Street	Main surchrged & blckd, Outlet pipe @M.H.being fix	Gwynns Falls	36	6:30 A.M. (5-31-05) - 6:30 P.M.(6-1-05)	Gray colored water	108000	Relieved using bypass pumping	Set up pump to by pass flow to clean the debris in line. Repair of M.H. Outlet pipe & line cleaning operation under way	SR # 10938, Reason: Sewer Main surcharged & blocked due to debris in line / Broken Outlet pipe @M.H.under repair

Table 4-2. Capacity-Related SSO Records in HLSS											
Place ID	Date of Occurrence	Location	Reason	Stream affected	Duration (hr)	Time	Description of Discharge	Estimated Quantity (gal)	Measures Taken to Minimize Discharge	Preventive Actions to Stop Recurrences	REMARKS
C	6/3/2005	2803 Dukeland Street	Main surchrged & blckd, Outlet pipe @M.H.being fix	Gwynns Falls	3	7:20 A.M. - 10:30 A.M.	Gray colored water	16150	Relieved using bypass pumping	Set up pump to by pass flow to clean the debris in line. Repair of M.H. Outlet pipe & line cleaning operation under way	SR # 10938, Reason: Sewer Main surcharged & blocked due to debris in line / Broken Outlet pipe @M.H.under repair
C	7/8/2005	2803 Dukeland Street	Main surcharged bc heavy rain & overflow@M.H.	Gwynns Falls	2	8:00 A.M. - 9:34 A.M.	Heavy gray colored water.	9400	None, Overflow stopped naturally	This line is required to be monitored & be placed on Preventative Maintenance schedule if necessary	SR # 13491, Reason: Sewer Main surcharged due to heavy rain & overflow at the manhole occurred.
C	1/14/2005	2803 Dukeland street	Heavy Rain	Gwynns Falls	12	11:00 A.M.(1-14-05) - 11:00 P.M.(1-14-05)	Gray colored water	72000	------	This sewer main is required to be reevaluated, be monitored & be placed on Preventative Maintenance Schedule if necessa	SR # 3968
D	10/15/2003	3000 Gwynns Falls Parkway	Grease and rags	Gwynns Falls	2	8:00-10:00	Light gray water	1200	Used jet and cutter to relieve and clean 8" sanitary mainline	Line will be monitored and placed on a preventive maintenance regime if necessary	None
D	10/13/2005	3000 Gwynns Falls Parkway	Via Stom Draip?	Middle Branch	1	8:30P.M. 10/13/05-10:15P.M.10/13/05	Grey Water	1575	Used Jet to Reduce?		None
D	2/12/2006	3000 Gwynns Falls Parkway	Stru:Sewer Manhole. Rags,Grease,Sand,Gravel, Rock	Gwynn Falls Parkway	5	9:00P.M. 2/12/06 to 2/13/06 2AM	Brown, Gwynn	1200	Used	2/12/06 9 PM to 2/13/06 2 PM	None
E	5/24/2004	1200 Braddish Avenue	Choked 39" sanitary mainline	Gwynns Falls	0	13:00 - ?	Heavy gray water	33000000	Video inspected and attempted to relieve with jet	Nothing	None
E	6/23/2004	1200 Braddish Avenue	Blow Type Bulk Head Failed	Gwynns Falls	5	9:55 - 15:20	Heavy gray water	9750	Removed the damaged bulk head and replaced it with a new one	Line will be monitored and placed on a preventative maintenance regime if necessary	None
E	7/2/2004	1200 Braddish Avenue	Rags, Roots, Trash, Railed ?	Gwynns Falls	5	6:00 A.M. 7/2/04-11:00 A.M. 7/3/04	Rags, Roots, Trash, Railed Bulk head due to Drainage 18" Overflow Pipe	36	Replaced Bulkhead. Install brick cap into 18" overflow Pipe		Est. Quantity Discharge 36.25 M.G.D. , SR# 197325

Table 4-2. Capacity-Related SSO Records in HLSS

Place ID	Date of Occurrence	Location	Reason	Stream affected	Duration (hr)	Time	Description of Discharge	Estimated Quantity (gal)	Measures Taken to Minimize Discharge	Preventive Actions to Stop Recurrences	REMARKS
E	10/12/2005	1200 Braddish Avenue	Sewer Manhole, Rags, Roots	Middle Branch	19	6:00A.M. 10/12/05-3:15 A.M. 10/13/05	Gray water	8325	Used jet		None

Sewer Complaints:

Another set of SSO-related records was provided by the City's technical management team, SC 1015. This dataset contained over 4,000 sewer-related complaints that the City had received between November 2004 and December 2007. The problems were grouped into the following categories: sewage in basement, sewer overflow, sewer leak, and miscellaneous. The modeling team did not actively use these records for model development because the dataset lacked important information such as the reason for blockage/overflow and any remedial measures undertaken by the City.

Baltimore City Detention Center (BCDC) SSO:

The overflow location in front of the Baltimore City Detention Center (400 East Eager Street) is a capacity-related and recurring SSO. This SSO location is not included in the CSO/SSO notification records. Instead, it was brought to the City's attention through a sewer complaint e-mail to Mayor Sheila Dixon that specifically referred to an overflow that occurred on February 1, 2008. This e-mail indicated that this overflow location had recurring problems by using qualifiers such as "had been chronic," "painfully obvious…," "for years…," and "whenever we get a good soaking hard rain…" The HLSS team conducted further investigation of this SSO location through site visits and flow data/scatter plot analysis. This investigation report was submitted separately to the City in April 2008. The BCDC investigation revealed that the HLI had experienced frequent surcharges and several potential SSO locations exist due to capacity limitations.

4.1.3 GIS Data in HLSS

The City maintains and updates various types of GIS data. This database, called the City of Baltimore Wastewater GIS, includes the City's wastewater service information such as sewer attributes, manhole junctions, house connections, and pump stations. Additional data such as the elevation, population, streets, and buildings have been compiled from several original data sources. This section describes the data used for hydraulic model development and calibration.

As-Built Drawings:

The City's Automated Image Retrieval System (AIRS) is a tool that facilitates the search process for digital image documents such as water and wastewater infrastructure drawings (as-built drawings). This tool was used extensively by the HLSS team to obtain as-built drawings during model development whenever questions arose about sewer connectivity, pipe sizes, and pipe slopes.

Figures 4-6 and 4-7 are examples of as-built drawings compiled from AIRS that were critical for model construction. Figure 4-6 shows the profile of the triple-barrel HLI inverted siphon. No data was available from field surveys for this siphon since it was flowing full continuously. Therefore, the pipe size, length, and invert elevation at all the siphon bends were obtained from this drawing.

Similarly, Figure 4-7 shows the profile of a section of HLI that had large pipe sizes from 52” to 100” in diameter. This pipe section was also very flat, with sediment depths ranging from one-quarter to half of the pipe diameter. This condition made the pipe size and invert depth calculations cumbersome and uncertain based on field measurements. As such, the profile data from as-built drawings was used for model development instead of the field survey data.

Population:

The United States Census Bureau gathered census data in 2000 which is available in a GIS format. This data was accessible for each small census block in HLSS. In order to obtain a reasonable population estimate for each flow basin, the basin boundaries were overlaid with census blocks to make finer fractions. The population for each census block fraction was determined based on the area proportion within the flow basin. The total estimated population within a basin was calculated by adding the population of all whole blocks and all fractions within the basin. A schematic of this process is shown in Figure 4-8.

Figure 4-9 shows the processed population density for each flow meter basin. Fewer people live in flow basins in the middle of GRI where there are large public spaces (e.g., Hanlon Park and Lake Ashburton) and several large business facilities (e.g., Ashburton WFP and Baltimore City Community College). The remainder of HLSS drainage area is mostly residential. As seen in the figure, the population density is lower in the north where each house has relatively larger lot size and higher in the south where there are predominately smaller houses.

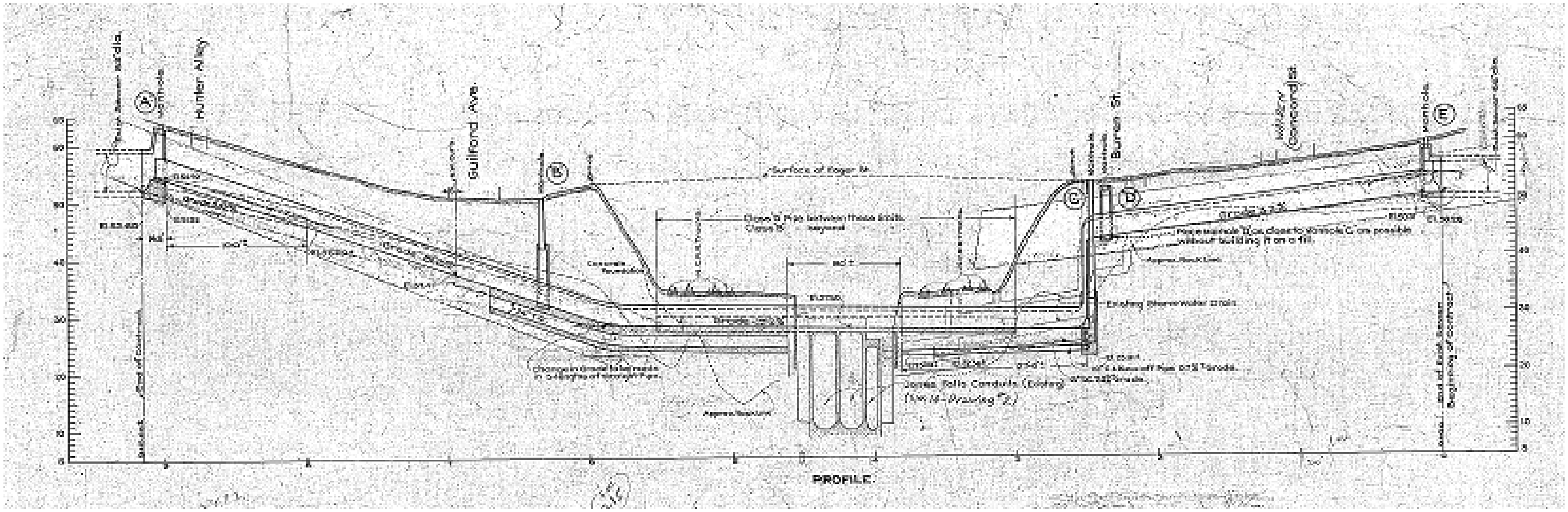


Figure 4-6. HLI Inverted Siphon profile

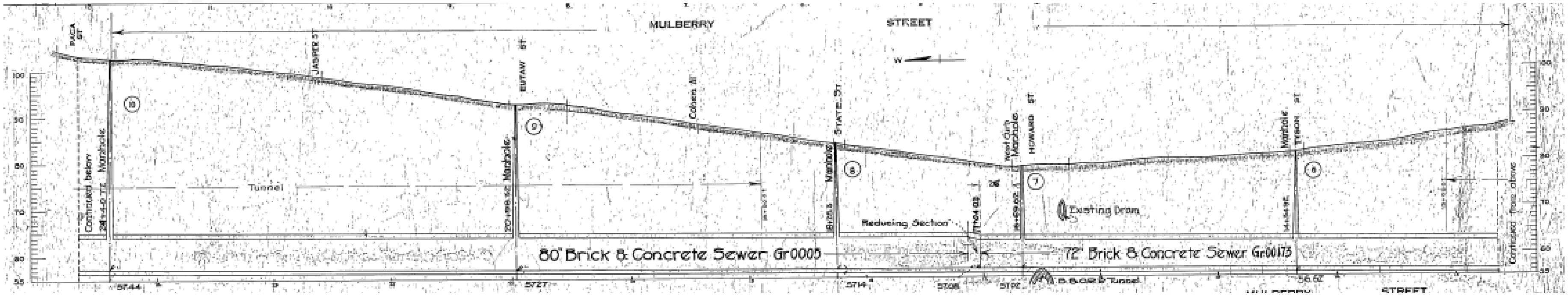
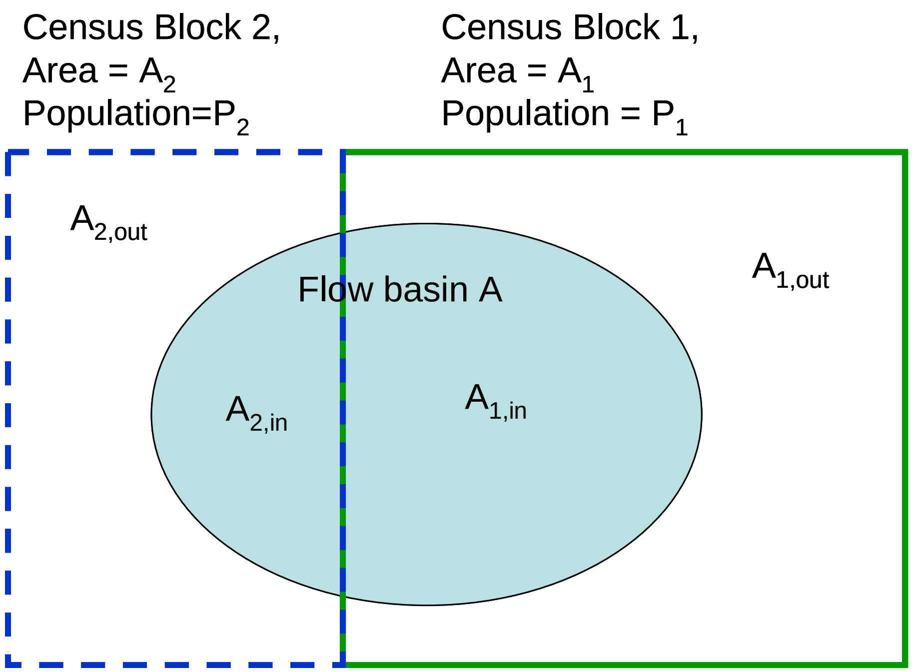


Figure 4-7. HLI profile from as-built drawing



Outside of flow basin A, but inside of census block 1, Area = $A_{1,out}$
Inside of flow basin A, and inside of census block 1, Area = $A_{1,in}$
Outside of flow basin A, but inside of census block 2, Area = $A_{2,out}$
Inside of flow basin A, and inside of census block 2, Area = $A_{2,in}$

Population of flow basin A =

$$P_A = \frac{A_{1,in} + A_{1,out}}{A_1} \cdot P_1 + \frac{A_{2,in} + A_{2,out}}{A_2} \cdot P_2$$

Figure 4-8. Population Processing in GIS

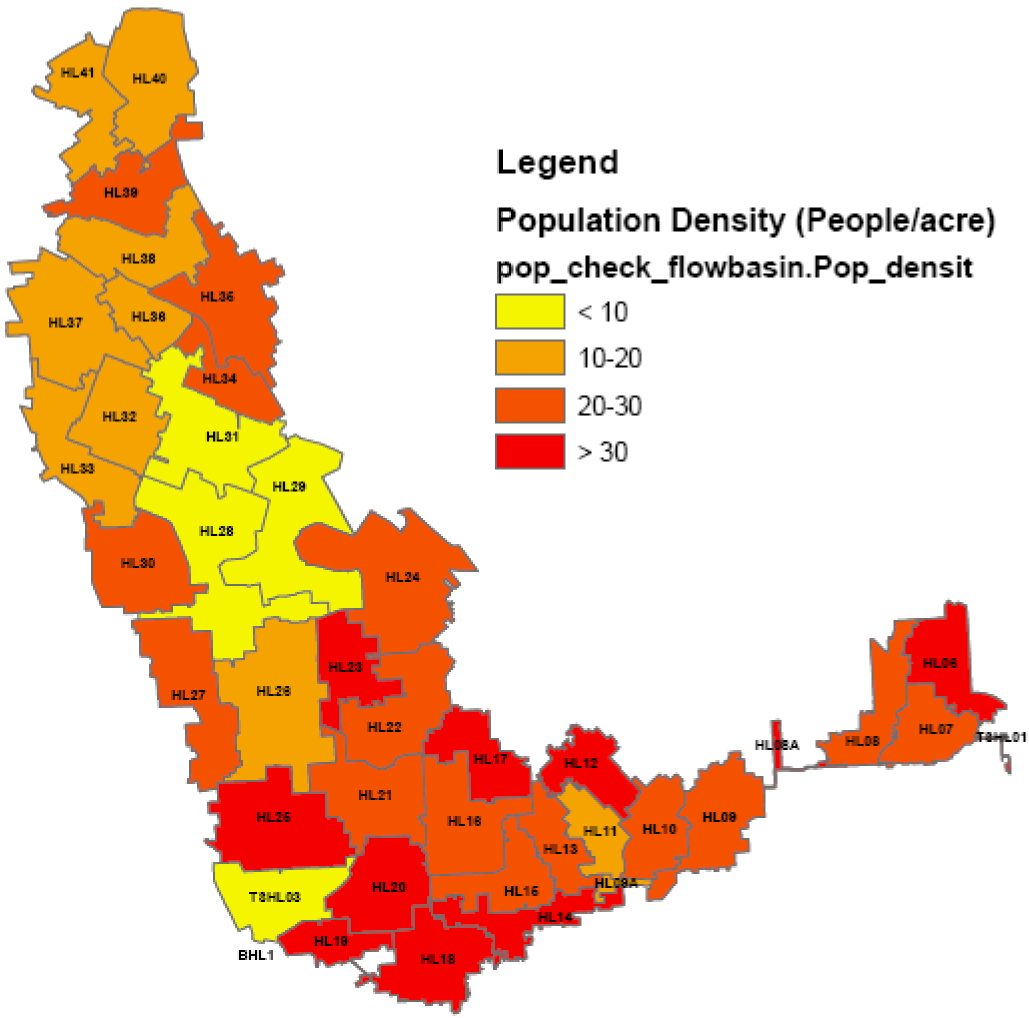


Figure 4-9. Population density in HLSS based on Census 2000

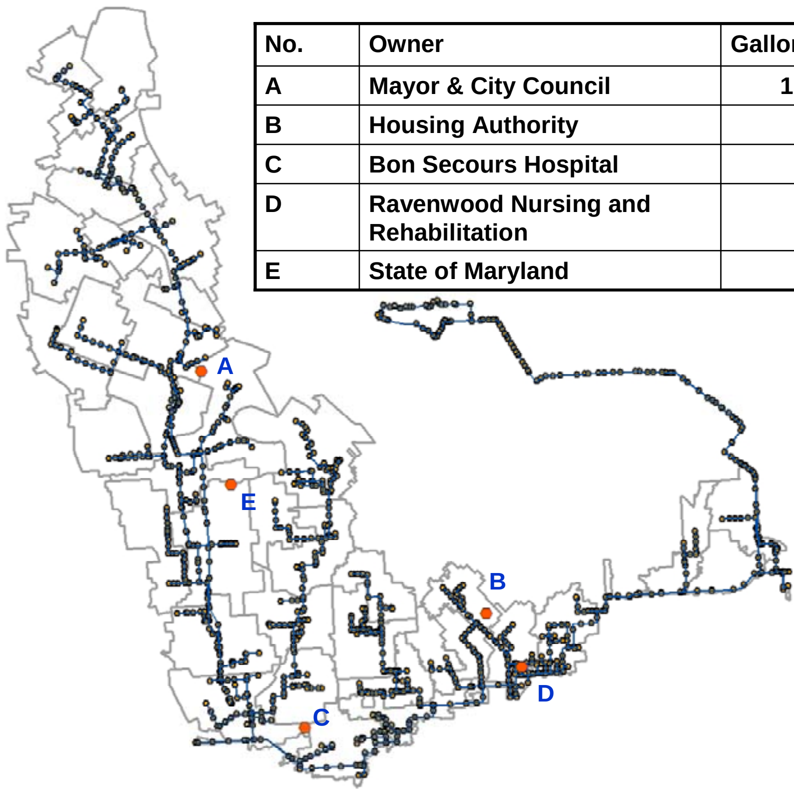
Elevation:

There are two elevation data sources available: the National Elevation Dataset (NED) distributed by the USGS and the spot elevation developed by the City. The NED data has elevations for each grid of 30 m by 30 m (approximately 100 ft by 100 ft) in size. The City's spot elevation data is available at a much finer resolution (approximately one spot for every 200 ft^2, or 14.1 by 14.1 ft), but unevenly distributed throughout the City. Therefore, a new elevation grid with 15 by 15 ft cell size was created in GIS based on the spot elevation data.

The elevation data was used to calculate the ground surface slope for each modeled subcatchment. The other use for elevation data was the ground level assignment for the modeled manholes that were not accessible during field surveys (e.g., in private property or covered by dense vegetation).

Significant Water Users:

The City maintains a database of significant water users and their yearly water consumption rates. As part of the City's databases to support the HLSS study, the top 100 water users and their water consumption rates were provided to the HLSS team. Figure 4-10 shows the top five users. The maximum water user was the Ashburton WFP which consumed approximately 1.7 MG of water on a daily basis. The daily consumption for the other top 100 water users ranged from 8,000 to 112,000 gallons. Since all water users except the Ashburton WFP consumed less than 120,000 gallons per day, the HLSS team assumed that those flows would not overwhelm the local sewers and, therefore, those water users were not included as additional point dischargers. These discharges however were figured into the total DWF for each flow basin. This process is described further in Section 5.3.



No.	Owner	Gallons / day
A	Mayor & City Council	1,680,000
B	Housing Authority	112,000
C	Bon Secours Hospital	99,000
D	Ravenwood Nursing and Rehabilitation	72,000
E	State of Maryland	71,000

Figure 4-10. Top 5 Water Users in HLSS with their water consumption

Sewer and Manhole Junctions:

Sewer and manhole junction GIS data were not used extensively during model development since the field surveys, including land survey, manhole inspection, and CCTV inspection, covered most of the modeled sewer network. However, the sewer and manhole junction data were used when the model subcatchments were delineated for the entire HLSS network including the 8” pipes.

Street and Building Polygons:

The street and building polygons from the City GIS were used during model subcatchment delineations so that the resulting boundaries would depend both on the sewer network and surface structures that could influence the drainage patterns.

Aerial Photos:

The aerial photos provided by the City were often used to form a better understanding of the sewershed areas. For example, when a large area was assigned a very low population density, the HLSS team was able to check the corresponding aerial photos to verify if a large portion of the area was occupied by open spaces such as parks and woods.

4.1.4 Field Data Collection

As part of the HLSS study, five types of field data collection were conducted by the ADS/JMT Joint Venture and its subconsultants: land surveys, manhole inspections, CCTV inspection of all sewers, sonar inspection of large sewers, and smoke testing to identify sources of inflow/infiltration. Some of these field activities are necessary to meet the CD requirements. However, all of these efforts are intended to support the characterization of localized and system-wide hydraulic capacity limitations so that appropriate rehabilitation strategies can be developed by the HLSS team. Each of these efforts is described below.

Land Surveys

Most of the HLSS manholes including those incorporated into the hydraulic model (generally connecting pipes 10” and larger) have been land surveyed. The land survey crew used a handheld global positioning system (GPS) device that recorded the X, Y and Z coordinates for a given manhole, where the Z coordinate corresponded to the rim elevation of the manhole. The X and Y coordinates were based on a NAD83/NAVD88 geographical coordinate system, which is compatible with the City’s GIS database systems.

The following data was collected:

- Manhole ID Number (e.g. S25GG_017MH)
- Manhole Cover Center Coordinates (X, Y and Z)
- Date of Survey
- Initials of Survey Crew

Some manholes that are located on private properties or near railroads, as well as those heavily covered by dirt or dense vegetation were not surveyed in the first phase of this process. A request for information (RFI) was sent to the City requesting permission to gain access to the manholes within or close to private properties and railroads. For manholes that were not detectable using the GPS or traditional survey techniques, data was obtained from various available sources (e.g., the macro model and digital elevation model (DEM) in GIS format).

As part of model development, manhole rim elevations obtained from land surveys were imported into the model to provide accurate ground level representation for all the modeled manholes.

Manhole Inspections

Manhole inspections involved verification of the sewer system attributes such as pipe diameters, depth to manhole inverts, network connectivity and any missing sewer system configurations. During these inspections field crews found structures that were not recorded on City maps. These findings were used to update the sewershed mapping. The inspections were carried out in accordance with the EPA's SSES (Sewer System Evaluation Survey) Handbook and the National Association of Sewer Services Companies (NASSCO) Manhole Assessment and Certification Program (MACP) guidelines. These could also provide defect and observation data for condition assessment.

The data gathered in the field has been transferred to digital manhole inspection summary sheets. The City provided a standardized manhole inspection application, Manhole Inspection Application Software (MIAS), for this purpose.

MIAS organizes the data collection and data entry into the City's databases. The MIAS database includes detailed information about the physical characteristics of each manhole, the sewer connections, and the manhole's surrounding structural and visual details. Besides collecting information such as size, shape, and material, the inspections also record manhole defects and potential sources of inflow/infiltration. The MIAS application provides a method to link photos of a manhole's features and defects to its database record. MIAS also includes several interfaces that allowed users to perform queries, process image files and manage the collected manhole data. ADS/JMT completed a QC process that included data collection check (i.e., whether a single inspection includes all the necessary data), data quality check (e.g., picture quality), and connectivity check (i.e., whether connecting manhole IDs are all correct).

Manholes that could not be located or could not be opened were reported to the City through an RFI process. These manholes were then resolved by reviewing the existing

CCTV data to help locate them. In the event that a manhole was surcharging and a full inspection could not take place, it was revisited when the flow levels were minimal.

The manhole inspections were performed from the ground level by inserting a camera installed on a long pole. As such, these inspections could not identify the extent of potential silt or debris accumulation in the manhole chambers. The survey crew lowered a pole into the manhole to determine the manhole depth. Since the ground level was accurately known from land survey, the manhole invert elevation was determined by subtracting the manhole depth from ground elevation.

CCTV Inspections

The CCTV inspection of sewer lines involves examining the interior of sewer lines to identify any existing or potential structural problems and their approximate locations. It can also provide information on previous lining projects, point repairs, improper or illegal connections, and potential sources and extent of I/I. This information will be used by the HLSS team and the City to determine the appropriate methods of repair, rehabilitation or replacement of sewer lines.

The CD requires that all gravity lines that are 8 inches and larger be inspected using CCTV, in accordance with the EPA Handbook and NASSCO guidelines. The PACP (Pipeline Assessment Certification Program) condition grading system, designed by NASSCO, provides standardization and consistency in sanitary sewer evaluation. Standardized coding allows pipe conditions to be compared from one time frame to another and from one location to another, if needed. The PACP system assigns a code for each structural defect and each operational and maintenance defect identified in the pipe. Each pre-defined defect/observation code is associated with a severity rating based on the type and extent of the defect. One use of CCTV data is to identify pipes which need immediate rehabilitation (e.g., heavy cleaning for pipes filled with accumulated grease). Another use of CCTV data is to prioritize pipes for rehabilitation. This process, referred to as the condition and criticality assessment, is being done system-wide by the HLSS team using GIS tools.

CCTV data can be utilized to refine the hydraulic model. Pipe blockages due to debris, root balls, or grease can be incorporated into the model as pipe area reductions. Inflow and infiltration severity can be varied for each subcatchment due to the PACP ratings or number of major defects related to inflow and infiltration such as pipe collapse, joint offset, pipe holes, etc. These model refinements based on CCTV data will be carried out to identify local bottleneck issues. This will allow the effectiveness of prioritized sewer rehabilitation can be assessed using the hydraulic model.

Sonar Inspection:

Sonar inspection, in conjunction with CCTV inspection, is used to assess the conditions of large diameter trunk sewers where the large depths of flow can wash away the traditional CCTV equipment. The primary use of sonar equipment is to inspect the structural condition of otherwise inaccessible or flooded sections of sewers. In particular, sonar technology allows inspection of sewer cross-sections below the water line which provides the depth of sediment.

In HLSS, most of HLI and the downstream portion of GRI were inspected using sonar technology. The observed sediment depth was imported into the model for every pipe segment. An example of a sonar inspection image is shown in Figure 4-11. In this image, sediment accumulation is almost 2 feet in this 8-foot diameter pipe section.

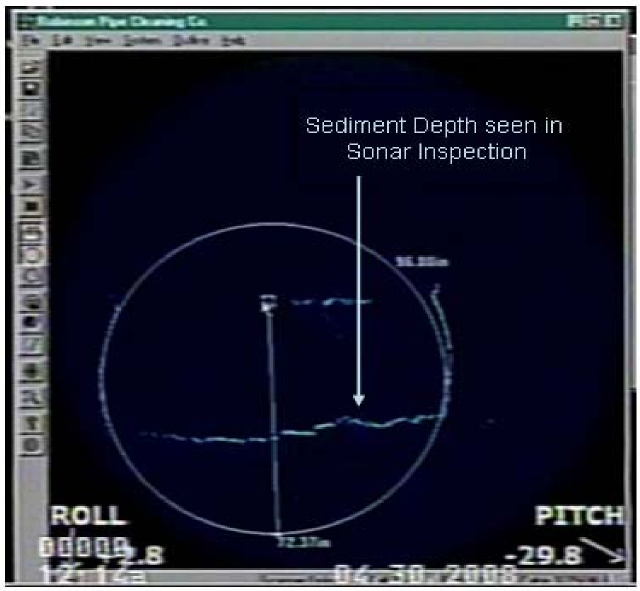


Figure 4-11. Sonar Inspection showing Sediment Depth at Pipe in High-Level Interceptor

Smoke Testing:

Smoke testing involves the introduction of non-toxic smoke into a sewer line to locate direct inflow sources such as storm drains, sump pumps, roof leaders, and defects in main sewer lines or service laterals. The areas to be smoke tested in HLSS were chosen based on flow monitoring results and the magnitude of capture coefficients. For optimal results, the smoke testing was conducted during dry periods, with non-frozen ground conditions.

In HLSS, smoke testing is being conducted for 280,000 linear feet of sewer lines, which does not cover the entire study area. Several flow basins have been prioritized for smoke testing based on the RDII severity and available SSO records. As of December 2008, smoke testing has been completed in nine flow basins: HL30-36, HL27, and HL40.

4.1.5 City-wide Macro Model

The Baltimore City's sewershed hydraulic model development has been conducted in two phases. In the first phase, a "macro model" that includes major components of the City's entire collection and conveyance system was developed by 1015. The macro model includes pipes generally 12 inches and larger in size, trunk and interceptor sewers, force mains and the large-capacity wastewater pump stations. It was constructed by 1015 from the data being collected and evaluated by the City's GIS Department as well as the City's existing models (e.g., the City's original capacity model and the GRI hydraulic model developed by ARRO Consultants). This formed the basis for the HLSS team to continue with the micro model development and refinement as the second phase.

The micro model network includes all pipes 10" and larger, in accordance with the City's CD requirements. Several 8" pipes were included to capture locations with historical SSO occurrences and known engineered SSO reliefs. The calibrated and validated micro model will be submitted to 1015 for eventual integration into a city-wide wastewater collection and transmission system model, to be used for regional I/I rehabilitation analyses. Figure 4-12 shows the macro model portion highlighted in orange on the whole extent of the micro model being calibrated by the HLSS team.

Figure 4-12. Macro Model Overlaid on HLSS Micro Model Network

4.1.6 Engineered SSO Locations

An engineered SSO in the City of Baltimore is a constructed cross-connection pipe between sanitary and storm sewers to alleviate localized surcharging/flooding of sanitary sewers until the rehabilitation projects under Paragraph 8 are completed. Upon completion of the projects, these engineered SSOs will be eliminated. The City has installed dedicated real-time flow monitors to track whether these locations had active overflows prior to and during the Paragraph 8 rehabilitation projects. There are a total of 16 documented engineered SSO locations in HLSS, and three of them remain active as of November 2008.

Engineered SSOs in HLSS

Table 4-3 shows the list of all the documented engineered SSOs in HLSS. Also shown are the periods during which these locations have been active. The dates for completion of pertinent rehabilitation projects, and the associated elimination of the engineered SSO locations, were provided by the City and 1015. Of the 16 engineered SSOs in HLSS, 12 were active during the entire primary flow monitoring period of May 2006 through May 2007. All 12 locations were included in the hydraulic model.

Paragraph 8 Flow Monitoring

Short-term flow monitoring was conducted at some engineered SSO locations under the Paragraph 8 project. Table 4-4 shows the list of engineered SSOs and the corresponding periods for which the flow records were available. Monitoring data available for periods outside of the primary monitoring period (May 2006 to May 2007) was used to gain a better understanding of the frequency of overflow events. However, monitoring data available during the primary monitoring period (i.e., SSO 57, 126, 128, and 131 for the period between 9/1/06 and 2/28/07) was used for model calibration.

Table 4-3. List of Engineered SSOs in HLSS

		2006								2007												2008
		May	June	July	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	
SSO #	Sewershed	Primary Flow Monitoring Period																				
55	HL39	Not eliminated Until June 26th 07														Eliminated						
56	HL38	Not eliminated Until June 26th 07														Eliminated						
57	HL38	Not eliminated Until June 26th 07														Eliminated						
60	HL32	Eliminated on April 12th 2006																				
63	HL31	Eliminated on April 12th 2006																				
103	HL32	Eliminated on April 12th 2006																				
106	HL26	Not eliminated Until Dec 5th 07																				Eliminated
107	HL26	Not eliminated Until Dec 5th 07																				Eliminated
126	HL37	Not eliminated Until June 26th 07														Eliminated						
127	HL37	Eliminated in 2004																				
128	HL37	Not eliminated Until June 26th 07														Eliminated						
130	HL34	Not eliminated until December 07																				Eliminated
131	HL38	Not eliminated Until June 26th 07														Eliminated						
132	HL33	Not eliminated																				
134	HL32	Not eliminated																				
135	HL32	Not eliminated																				

Table 4-4. List of Flow Monitored Engineered SSOs

SSO#	Flow Monitoring Period
55	2/15/05 – 3/31/06
56	2/4/05 – 3/31/06, 9/1/06 – 2/28/07
57	2/7/05 – 3/31/06, 9/1/06 – 2/28/07
131	2/9/05 – 3/31/06, 9/1/06 – 2/28/07
128	2/7/05 – 3/31/06, 9/1/06 – 2/28/07
126	2/5/05 – 3/31/06, 9/1/06 – 2/28/07
60	2/15/05 – 3/31/06
63	2/4/05 – 3/31/06
130	7/25/03 – 2/23/05

Active Engineered SSOs near Liberty Heights Avenue

The engineered SSOs 132, 134, and 135 are the only remaining active locations in HLSS (see Figure 4-13). The City must eliminate these SSOs to comply with the CD without causing excessive burden on the local sewer system hydraulics. However, monitoring data revealed that overflow events have been occurring frequently at both SSO 132 and 134 during medium to large wet weather events. Figure 4-14 is a scattergraph of the November 16, 2006 storm at SSO 134, monitored by the HL32 flow meter. This shows that the surcharge depth exceeded the overflow pipe invert level (12" from manhole invert) for more than 8 hours, which implies that there was an overflow through the engineered SSO for more than 8 hours. Figure 4-15 is a scattergraph of the November 16th storm at the HL33 flow meter, which is located about 45 feet downstream of the engineered SSO 132. The scattergraph shows flow velocity decreased significantly during the peak surcharge. This implies that there was a downstream flow restriction primarily due to pipe capacity limitation along Liberty Heights Avenue. Not only was the velocity drop, the surcharge depth bounded at about 124" from the invert of the pipe at HL33. This implies the surcharge was relieved by an overflow through the engineered SSO 132 since the surcharge depth of 124" is greater than the vertical length between the HL33 pipe invert and the engineered SSO 132's overflow pipe invert, which is approximately 105". They are the bases that HLSS team considers there were overflows through engineered SSO 132 and 134 for the November 16th storm, a typical 2-yr 6-hr storm.

In order to support the City with closure of these locations, localized monitoring, flow data analysis, and cost-effective SSO elimination plan/design development are being pursued by the HLSS team using the hydraulic model.

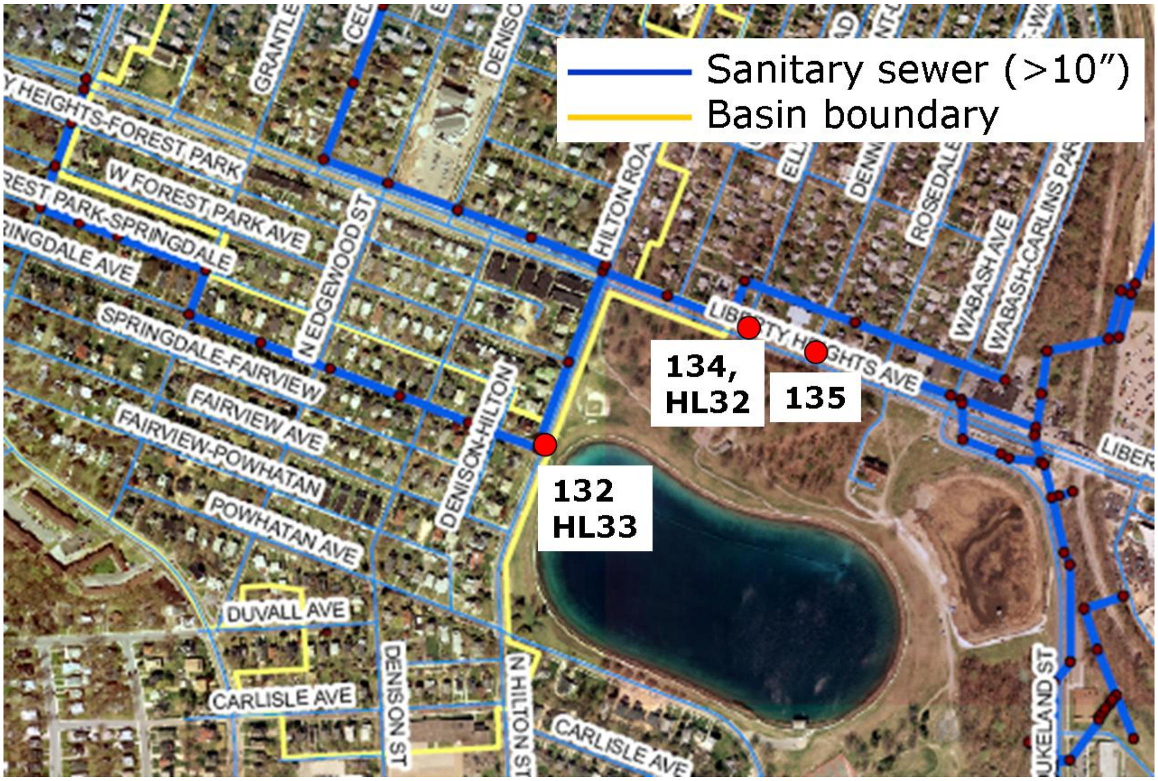


Figure 4-13. Aerial Photo Near Engineered SSOs 132, 134 and 135.

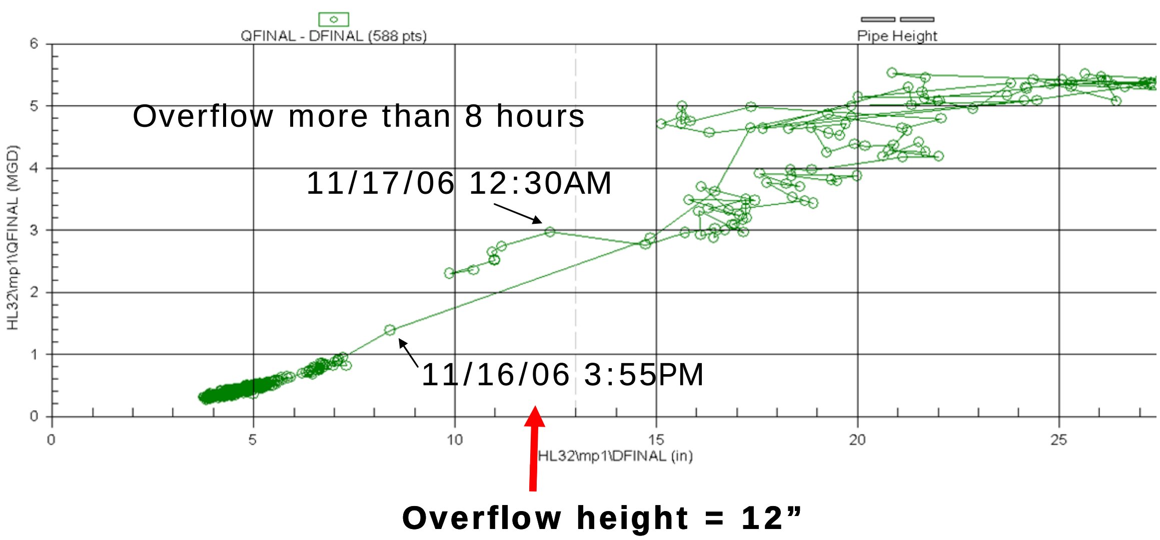


Figure 4-14. Scattergraph for November 16th Storm at Engineered SSO134.

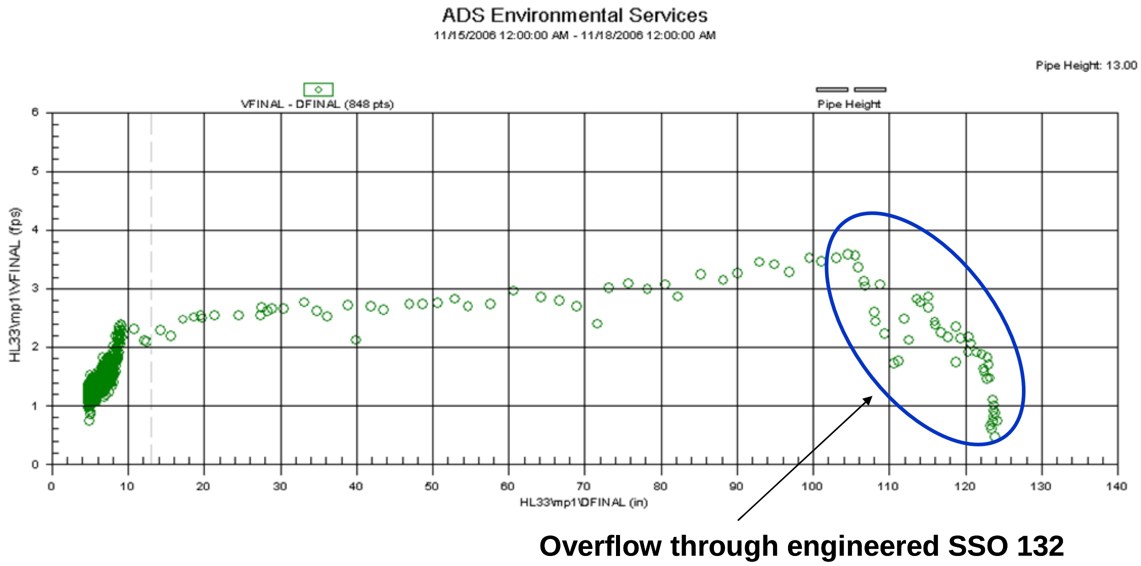


Figure 4-15. Scattergraph for November 16th Storm at HL33.

4.1.7 Reports and Protocols

The City provided the HLSS team with previous studies, maps, and as-built drawings for the development of the HLSS hydraulic model. The three main protocols used as guidance were the Consent Decree, the BaSES manual and the Scope of Work. These are briefly described in this section.

Consent Decree (CD): The CD is a legal binding document between the US EPA, MDE and the Mayor and City Council of Baltimore. This provided a set of regulations and procedures that the City of Baltimore must follow and outlined the rehabilitation measures needed to comply with the Clean Water Act.

BaSES Manual: The objective of the Baltimore Sewer Evaluation Standards (BaSES) manual is to provide technical guidance to each of the sewershed consultants working on a portion of the City's sewer system. The capacity analyses and associated hydraulic modeling are based on sound science; however, there could be variations in approaches between different technical consultants. This manual, created by 1015, aims at maintaining consistency among sewershed consultants. The manual provides guidelines for data collection, data analysis, model development and calibration.

Scope of Work: The scope of work for the HLSS team summarized the list of tasks and sub-tasks to be accomplished in each stage of the sewershed study. The major tasks are listed below:

a. Project Management.

b. Data Acquisition.

c. Regulatory Agency Coordination.

d. Public Information and Education Program.

e. Spatial and Tabular Database Management.

f. Sewer System Evaluation Survey (SSES).

g. Flow Monitoring and Rain Gauge Data Evaluation.

h. Capacity Evaluation and Hydraulic Modeling.

i. Infiltration and Inflow (I/I) Evaluation.

j. Sewershed Study and Plan.

k. List of Deliverables.

Specific approaches outlined in the scope of work and approved by the City have been used in the model calibration process, including the characterization of seasonal capture coefficients as discussed in Section 6.

4.2 RAINFALL MONITORING

Rainfall data is critical for hydraulic model calibration and I/I quantification. For I/I evaluation, rainfall data is used to determine the amount of total rainfall volume for each storm event and each basin and to calculate the ratio of RDII to the total rainfall volume. This ratio, known as the capture coefficient, is used to evaluate the severity of RDII. For hydraulic model calibration, rainfall data is used as wet weather event input to simulate the RDII responses.

In accordance with the CD requirements, the City had collected rain gauge adjusted Doppler Radar-rainfall data (known as the Radar rainfall data) as well as rain gauge data measured at several point locations in the City. Both Radar and rain gauge data were provided to each sewershed consultant by the City of Baltimore. The general recommendation from the City was to use the Radar rainfall data.

The HLSS team used all Radar rainfall events of 0.5 inches total depth within 24 hours for model calibration, except for those events during which the sewer flows were impacted by snowmelt. These major precipitation events, called global storms because they affected the entire service area, were pre-selected by 1014/1015 to establish consistency among individual sewersheds and also to support a regional model calibration once the individual sewershed calibrations are complete. These global storms and corresponding rainfall depths measured at three rain gauges near HLSS are shown in Table 4-5.

Some large global storms occurred on June 25, July 5, and November 16 in 2006 and March 15 and April 14 in 2007. Each of these major storms had approximately a 2-year 24-hour storm severity. These storms were frequently used for data analysis throughout this calibration.

Table 4-5. Storm Period and Depth for Global Storms

No.	Rain Start	Rain End	Storm Period (hr)	Strom Depth (in)		
				GF07RG	GF09RG	JF12RG
1	5/11/06 12:00	5/11/06 22:00	36	1.70	2.10	1.46
2	5/14/06 23:00	5/15/06 16:00	48	1.06	0.75	0.95
3	6/2/06 19:00	6/3/06 6:00	24	0.65	1.58	0.55
4	6/19/06 14:00	6/19/06 16:00	24	0.39	0.96	0.26
5	6/24/06 13:00	6/24/06 22:00	18	0.92	0.53	0.87
6	6/25/06 4:00	6/26/06 22:00	144	6.33	6.10	5.92
7	7/5/06 11:00	7/6/06 6:00	96	2.47	1.44	3.21
8	7/22/06 14:00	7/23/06 0:00	24	0.65	1.04	0.49
9	9/1/06 6:00	9/2/06 17:00	60	2.21	2.19	2.37
10	9/5/06 2:00	9/5/06 17:00	48	1.70	1.15	2.17
11	9/14/06 1:00	9/14/06 21:00	72	1.35	1.22	1.15
12	9/28/06 17:00	9/28/06 22:00	36	0.77	0.84	0.82
13	10/5/06 20:00	10/6/06 16:00	120	1.81	1.53	1.70
14	10/17/06 7:00	10/18/06 2:00	36	1.26	1.26	1.00
15	10/19/06 20:00	10/20/06 11:00	36	0.45	0.54	0.44
16	10/27/06 15:00	10/28/06 8:00	60	1.96	2.01	1.89
17	11/7/06 20:00	11/8/06 15:00	60	1.41	1.54	1.33
18	11/16/06 8:00	11/16/06 17:00	120	2.31	1.74	2.30
19	11/22/06 11:00	11/23/06 3:00	96	0.96	0.85	0.92
20	12/22/06 12:00	12/23/06 3:00	60	1.35	1.34	1.16
21	12/25/06 12:00	12/26/06 1:00	72	0.57	0.57	0.57
22	12/31/06 16:00	1/1/07 14:00	72	1.04	0.96	0.92
23	1/7/07 17:00	1/8/07 16:00	72	0.91	0.88	0.86
24	3/1/07 18:00	3/2/07 9:00	96	1.15	1.09	0.88
25	3/15/07 16:00	3/16/07 17:00	144	2.23	2.16	2.41
26	3/23/07 13:00	3/24/07 10:00	72	0.43	0.56	0.36
27	4/4/07 3:00	4/4/07 9:00	24	0.39	0.33	0.50
28	4/11/07 21:00	4/12/07 6:00	48	0.90	0.93	0.94
29	4/14/07 19:00	4/16/07 3:00	120	2.47	2.36	2.58

4.2.1 Rain Gauge Data

The Radar rainfall data were recommended by the City for model calibration, unless the consultants found evidence that the data were deficient. Rain gauges served two purposes for this work. The first use was in the selection of dry days for the dry day analysis and the second was for calibration of the Radar images provided by the Nation Weather Services Nexrad Radar.

The point gauges provided continuous rainfall measurements at short time intervals such as 5 to 15-minutes. The HLSS team utilized the rain gauge data to support the selection of dry periods for dry weather flow calibration, and to check the quality of Radar rainfall data, which were estimated from the point gauge records, in order to support the wet weather calibration.

Gauges in HLSS

There are three permanent rain gauges within or near the HLSS among a total of 20 gauges located throughout the City (Figure 4-16).

Spatial Variability

The HLSS has a total area of about 4,600 acres and the longest distance between north to south and west to east is approximately 27,000 feet. As shown in Table 4-5, there are significant differences in rainfall depth between these three rain gauges for some storms. This clearly indicates the presence of significant spatial variability in rainfall that can be important for accurate model calibration. In order to understand the extent of spatial differences in rainfall, depth-duration-frequency (DDF) curves were developed for two global storms (July 5 and November 16, 2006) as shown in Figures 4-17 and 4-18. For the July 5th storm, the total rain depth at the south gauge (JF-12 RG) was more than double that at the north gauge (GF-09). For the November 16th storm, the rain intensity in south and west gauges (JF-12 and GR-07) were much higher than that in the north gauge (GF-09). This spatial variability in rainfall supported the use of Radar rainfall data, which was available at a finer spatial resolution than the rain gauge data.

4.2.2 Radar Rainfall

The characteristics of Radar rainfall data differ from the rain gauge data in two ways: data duration and spatial availability. Radar data were provided by the City for each storm event, while continuous data was available for the rain gauges. This made the Radar data suitable for event-based simulations, but not necessarily for continuous simulation during the monitoring period. Finer spatial resolution was the primary advantage of Radar data, which was provided at a spatial resolution of 1 kilometer by 1 kilometer grid for the entire City. Figure 4-19 shows the Radar grid overlaid on the HLSS drainage area along with the locations of the point rain gauges. The Radar data were available for each of these pixels.

A single rainfall file was created for each Sewershed developing a weighted average of the pixel(s) in which the sewer shed resides. Based on the statistical correlations performed by the City, it was concluded that the Radar data was more accurate than the spatial interpolation of rain gauge data for portions of sewersheds far from any of the rain gauge locations. The HLSS team performed a random quality check of Radar data at or very near the point gauges. The result of the Radar data QC is described in detail in Section 6.

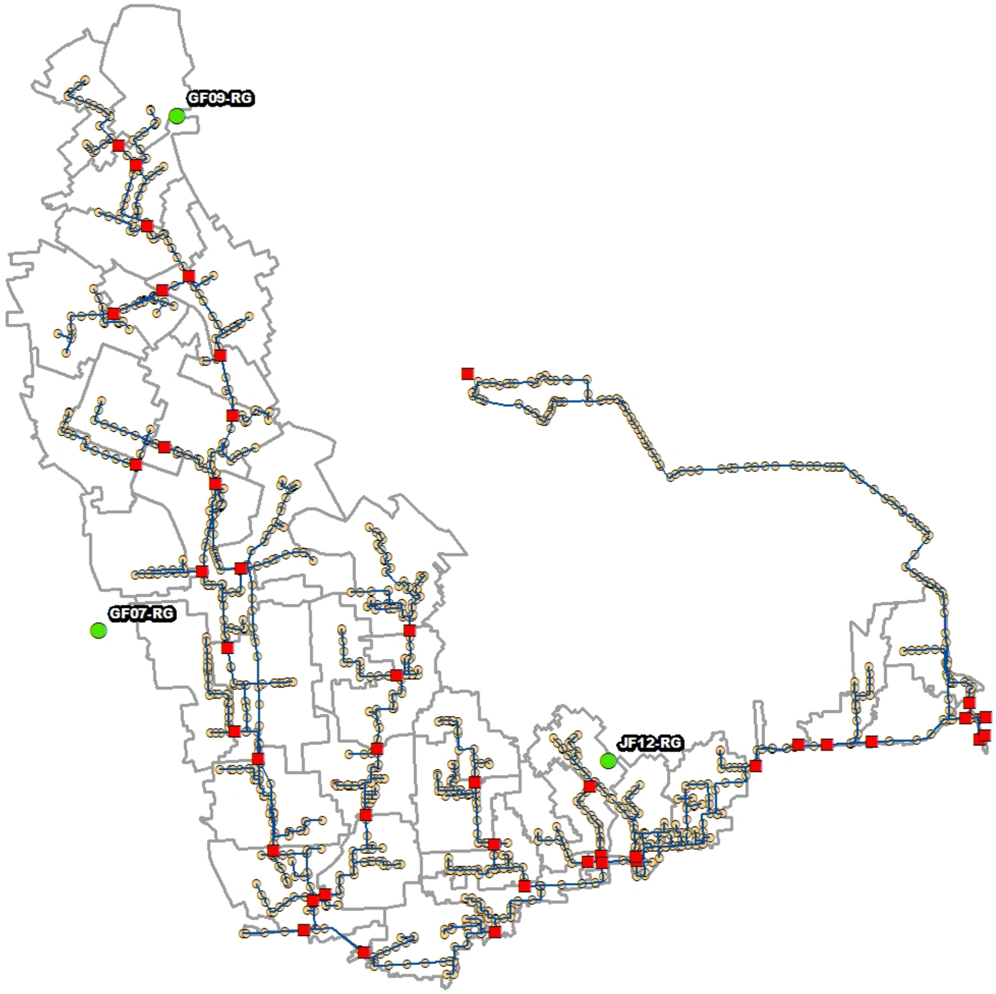


Figure 4-16. Rain gauge locations near HLSS

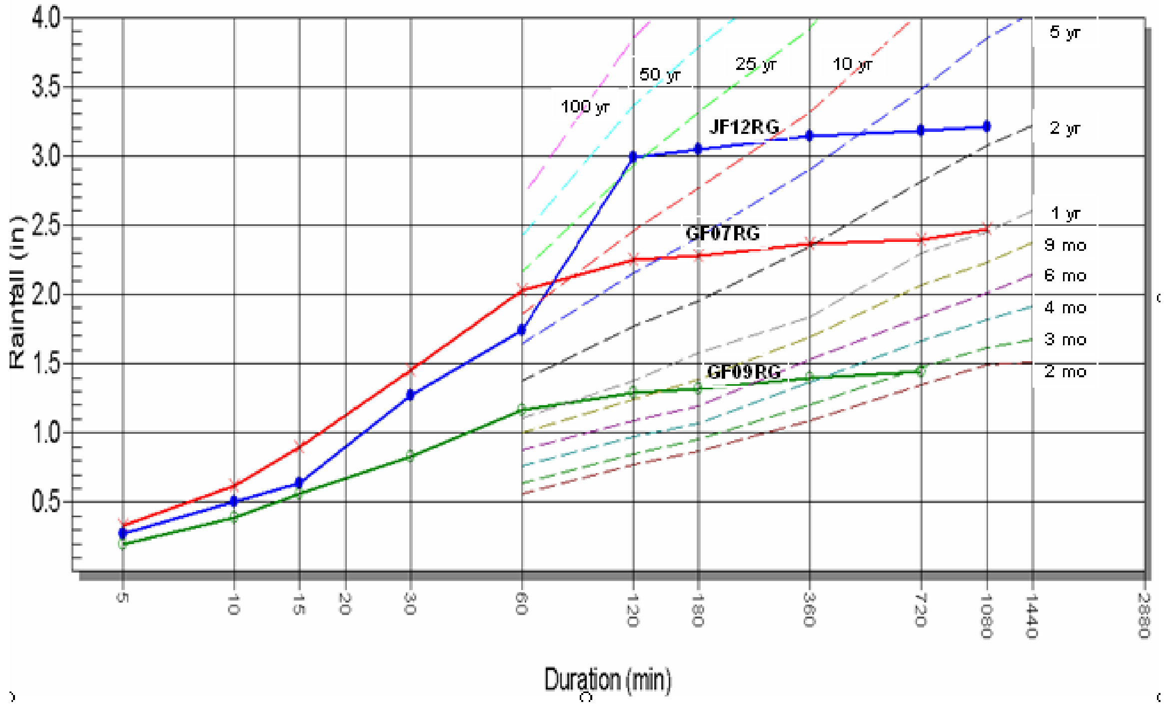


Figure 4-17. DDF Curves at three HLSS rain gauge locations for July 5th storm

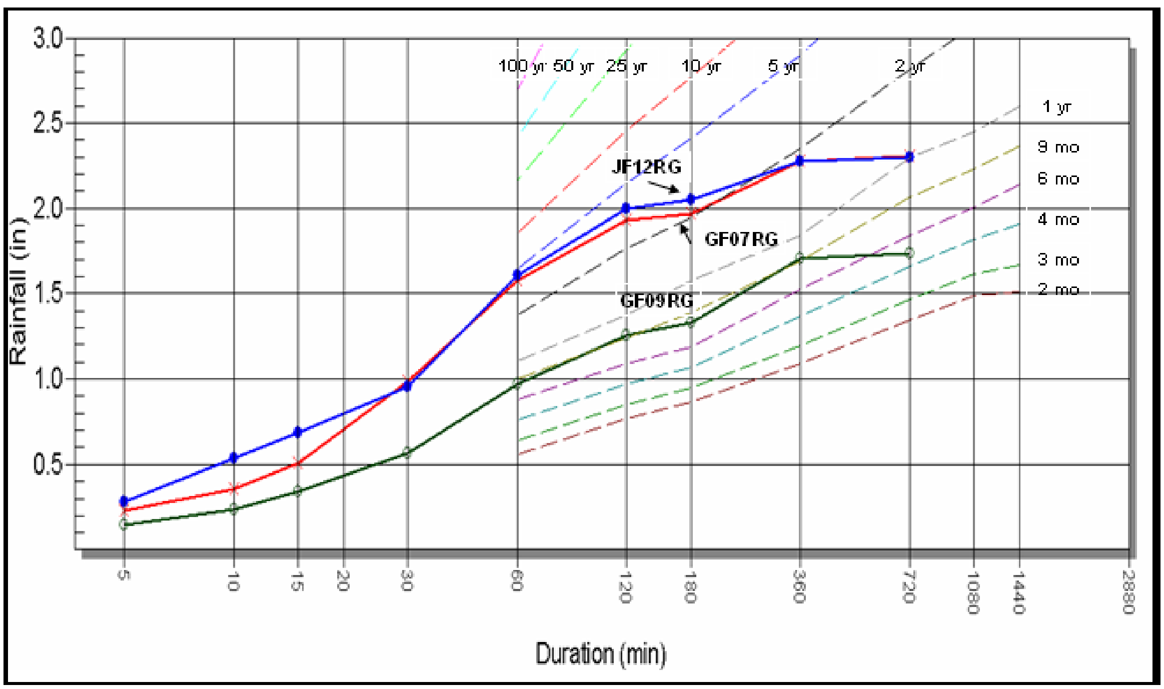


Figure 4-18. DDF Curves at three HLSS rain gauge locations for Nov 16th storm

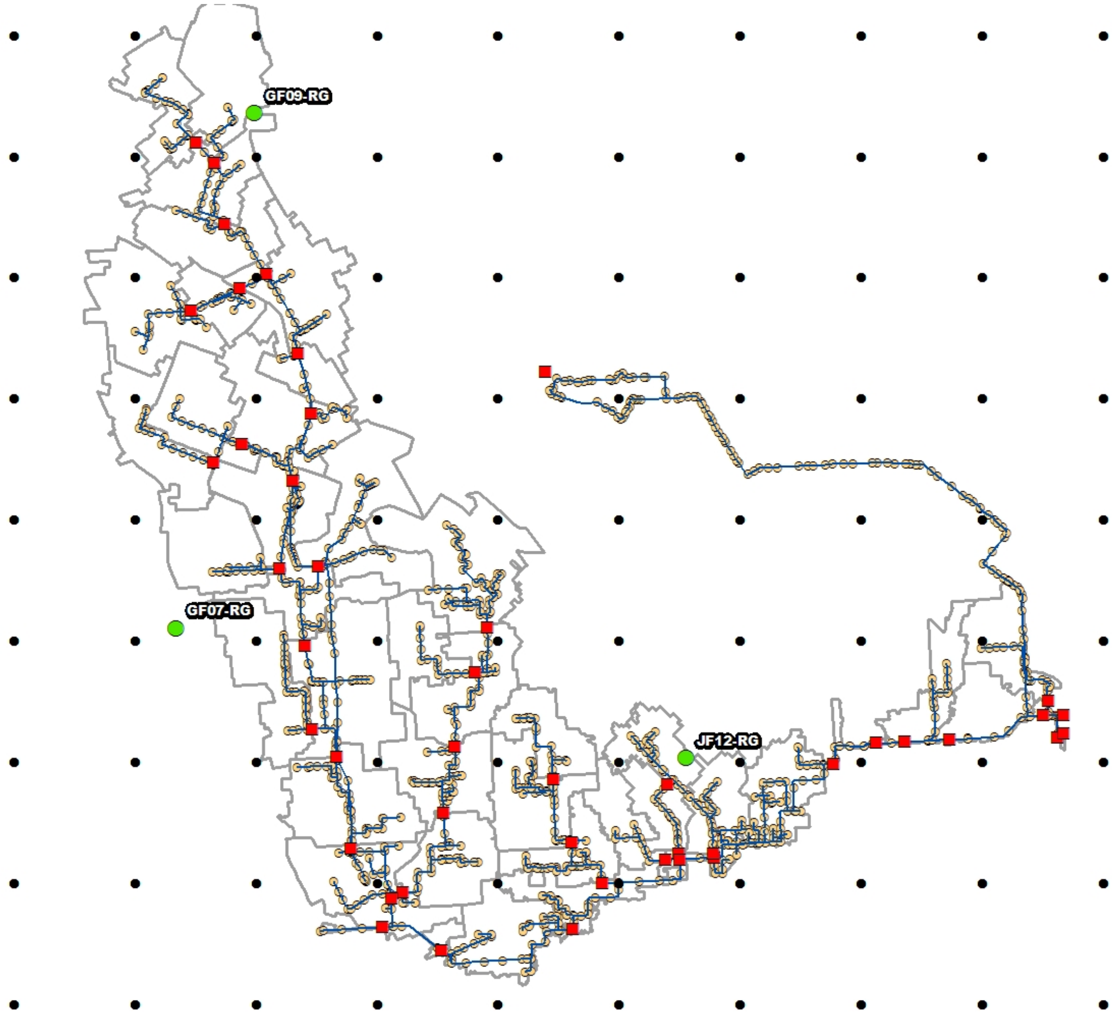


Figure 4-19. Radar Grid in HLSS

4.3 HYDRAULIC MONITORING DATA ANALYSIS AND ITS USE IN FLOW COMPONENT DEVELOPMENT

4.3.1 Sli/icer

Sli/icer is a data analysis and management tool used for analyzing I/I in sanitary sewer systems using rainfall and flow monitoring data. Similar to InfoWorks for citywide hydraulic modeling, the City has designated Sli/icer to be used for data analyses. One of Sli/icer's major advantages is the display of rainfall and flow data in various graphical windows which enable users to interpret the sewer hydraulic conditions. With 45 flow metering sites in place, HLSS had a vast amount of data collected from May 2006 to May 2007 that was analyzed using Sli/icer. In addition to the flow, water level, and velocity analyses, Sli/icer has other useful elements for rainfall analysis such as spatial averaging of point gauge data for each flow basin and graphical comparison between actual and design storms.

The HLSS Sli/icer database includes flow data from all flow meters within HLSS as well as the boundary meters (e.g., Lower Jones Falls Interceptor), and rain data for each flow basin. Both rain gauge and Radar data were available in Sli/icer, and either dataset could be selected to support the DWF and RDII analysis. Rainfall and flow data, depicted in Figure 4-20, could be exported for a specific duration (event or continuous periods) for further analysis and model input preparation. Sli/icer also has built-in functions to obtain both DWF and RDII parameters.

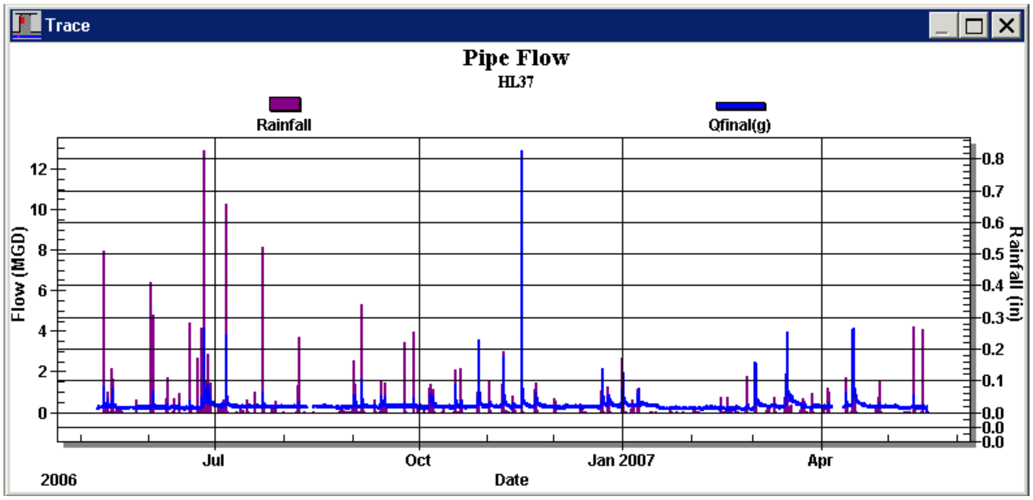


Figure 4-20. Flow data from May 2006 to May 2007

Global Setting:

Global setting is an important component of Sli/icer. It is a set of common rules to be applied to all the data processing in a Sli/icer database. Generally, these rules remain the same throughout a study in order to maintain consistency for data analysis. The global settings for HLSS include two seasons (summer and winter) for DWF and RDII determinations, storm dates, storm start time, RDII calculation period (24 hours for most storms), and the time steps for averaging (30 minutes) as shown in Figure 4-21. According to the global setting for seasons, the monitoring period was divided into three seasons: summer 2006, winter 2007 and summer 2007.

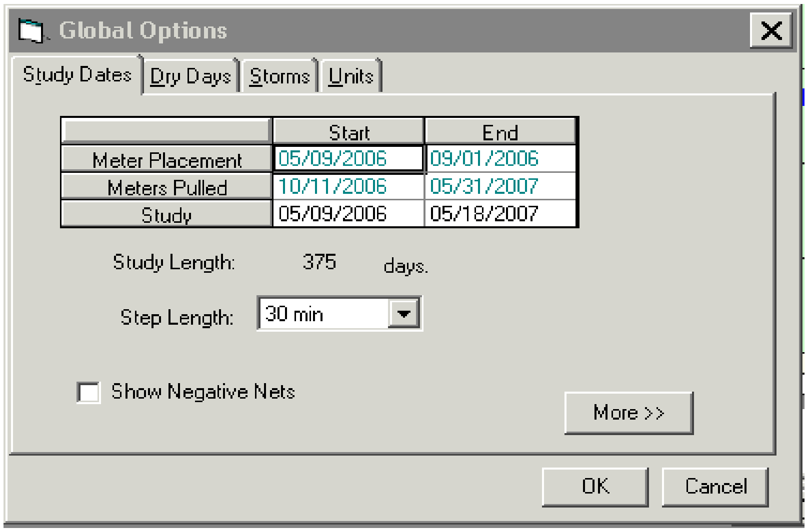


Figure 4-21. ***Global settings in Sli/icer***

Engineering Wizard:

The Engineering Wizard is a user control panel available in Sli/icer. This panel provides all available functional options to users in the form of tabs, drop down lists and tables (see Figure 4-22). Among these main tabs, the Rain and Meter tabs were frequently used by the HLSS team.

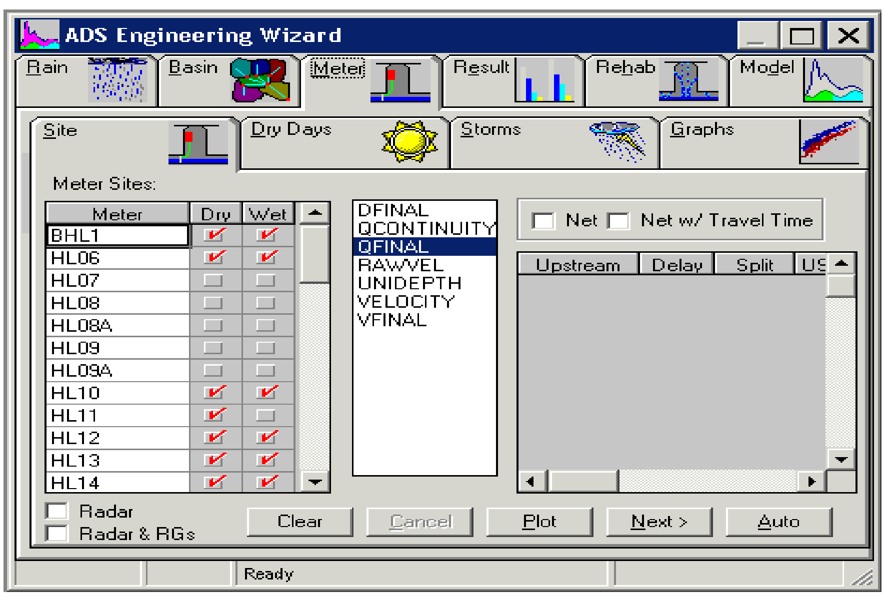
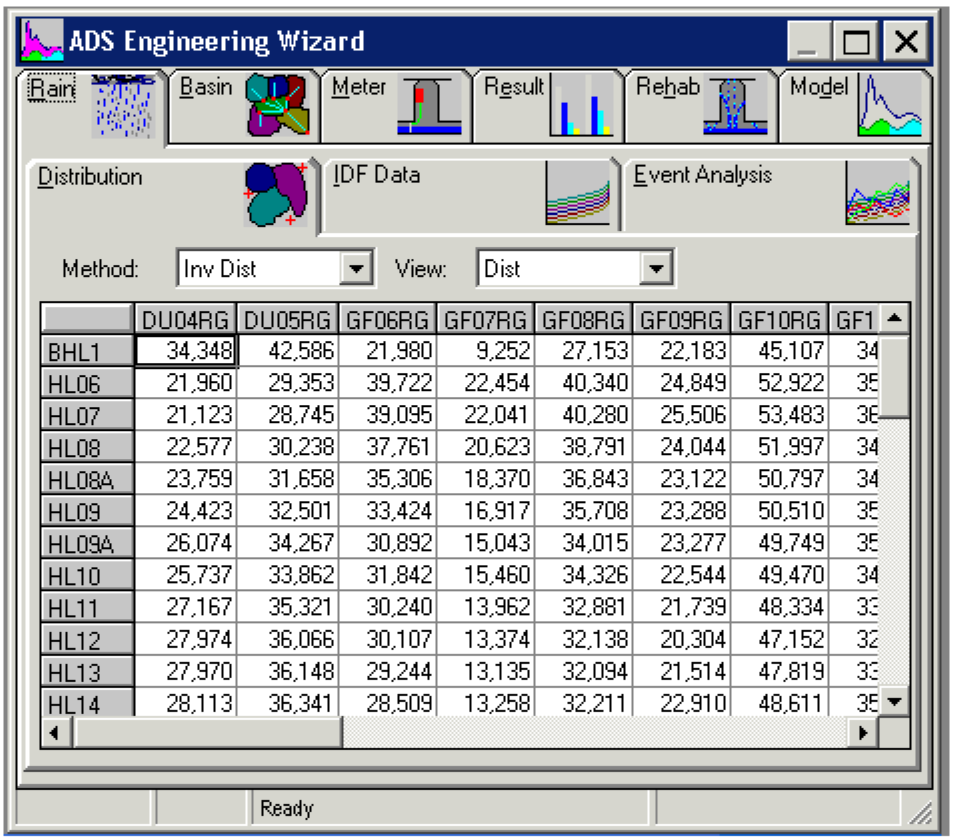


Figure 4-22. ***Engineering Wizard with functions under Meter Sub-tab***

Rain Tab:

The Rain tab allows a user to view data for any specific rain gauge. The sub-tabs are Distribution, IDF Data and Event Analysis as shown in Figure 4-23. The Distribution sub-tab provides the user with a range of rainfall spatial averaging methods. Spatial averaging is necessary since each meter basin is closer to some rain gauges than others. Sli/icer supports several different ways to weight rain gauges, including the Thiesses polygon, inverse distance, inverse distance square (quadrant), nearest (closest rain gauge), and a user-defined algorithm. For this study the inverse distance squared method was used along with the Radar rainfall data.

The IDF sub-tab contains several design storm depths specific for Baltimore City, the return frequency of which ranges from 2-month to 100-year with the durations from 1-hour to 24-hours. The Event Analysis tab stores rainfall depths for all storm events measured by the rain gauges.



	DU04RG	DU05RG	GF06RG	GF07RG	GF08RG	GF09RG	GF10RG	GF1
BHL1	34,348	42,586	21,980	9,252	27,153	22,183	45,107	34
HL06	21,960	29,353	39,722	22,454	40,340	24,849	52,922	35
HL07	21,123	28,745	39,095	22,041	40,280	25,506	53,483	3[illegible]
HL08	22,577	30,238	37,761	20,623	38,791	24,044	51,997	34
HL08A	23,759	31,658	35,306	18,370	36,843	23,122	50,797	34
HL09	24,423	32,501	33,424	16,917	35,708	23,288	50,510	35
HL09A	26,074	34,267	30,892	15,043	34,015	23,277	49,749	35
HL10	25,737	33,862	31,842	15,460	34,326	22,544	49,470	34
HL11	27,167	35,321	30,240	13,962	32,881	21,739	48,334	33
HL12	27,974	36,066	30,107	13,374	32,138	20,304	47,152	32
HL13	27,970	36,148	29,244	13,135	32,094	21,514	47,819	33
HL14	28,113	36,341	28,509	13,258	32,211	22,910	48,611	35

Figure 4-23. Rain tab with sub-tabs of Distribution, IDF Data, and Event Analysis.

Meter Tab:

The Meter tab displays data pertinent to each metering location. A specific site's data can be reviewed in detail to derive the appropriate I/I information. The Meter tab also provides a user with the option of either choosing a rain gauge or Radar rainfall data for wet weather analysis.

The four sub-tabs available under the Meter tab are: Site, Dry Days, Storms, and Graphs as shown previously in Figure 4-22. The Site sub-tab allows the user to choose a specific site and view data. The following section describes the remaining sub-tabs.

Dry Days Sub-Tab

This sub-tab enables a user to decompose the average dry day flow into WWP and BI and also to determine the diurnal pattern for each site, which is used as basis for calculating the wet weather flow. The DWF in the system is the sum of WWP and groundwater infiltration, which enters the system through sewer joints and cracks in the manhole walls.

The DWF patterns can be grouped in Sli/icer based on similar flow patterns. Each data group is called a day group (e.g., 2006 summer weekdays). For each monitored basin, Sli/icer analyses yield an average DWF hydrograph for each day group as shown in Figure 4-24, which depicts a significantly different diurnal pattern for the weekdays and weekend even in a single season (2006 summer). The average DWF and its diurnal pattern can be calculated from all the dry day flows for each day group. During this process, the HLSS team removed evident outliers from the DWF analysis using functions in Sli/icer.

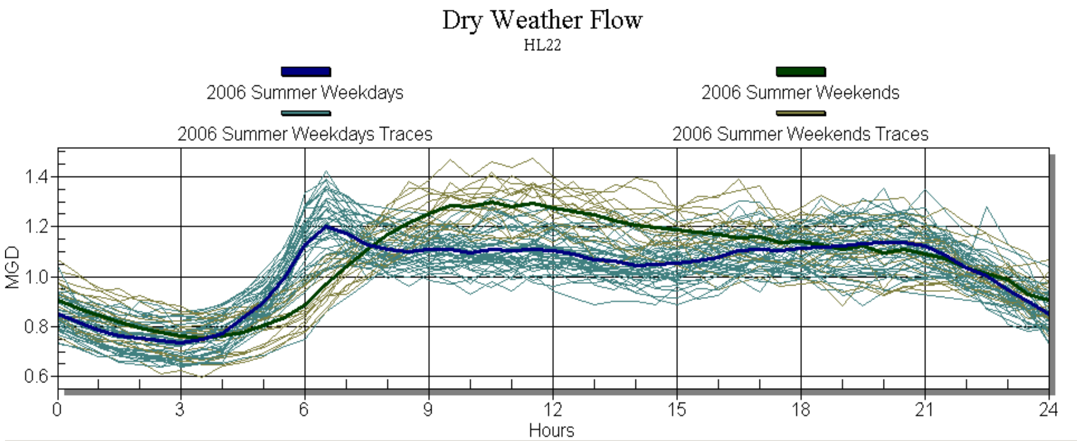


Figure 4-24. Weekday and weekend diurnal pattern with dry day traces from Sli/icer

Storms Sub-Tab:

In the Storms tab, the Sli/icer tool subtracts dry weather diurnal curves from the measured flow during storm events to determine the wet weather flow component. The storms tab uses the dry day and rainfall data to calculate the RDII volume for each storm event. In Figure 4-25, the average DWF is shown in green/blue which would be the actual flow if a storm had not occurred. The purple band shows the start and duration of the storm event. The blue line is actual flow recorded during the event and is the overall system response to this rainfall event. The RDII hydrograph is indicated in gold, which is the difference between measured flow and DWF. Pre-compensation is the adjustment of the dry day hydrograph to match the actual hydrograph immediately prior to the storm. The intention is to compensate natural variation in flow and periods of higher (or lower) ground water level influencing the DWF to be temporarily higher (or lower) than the average DWF.

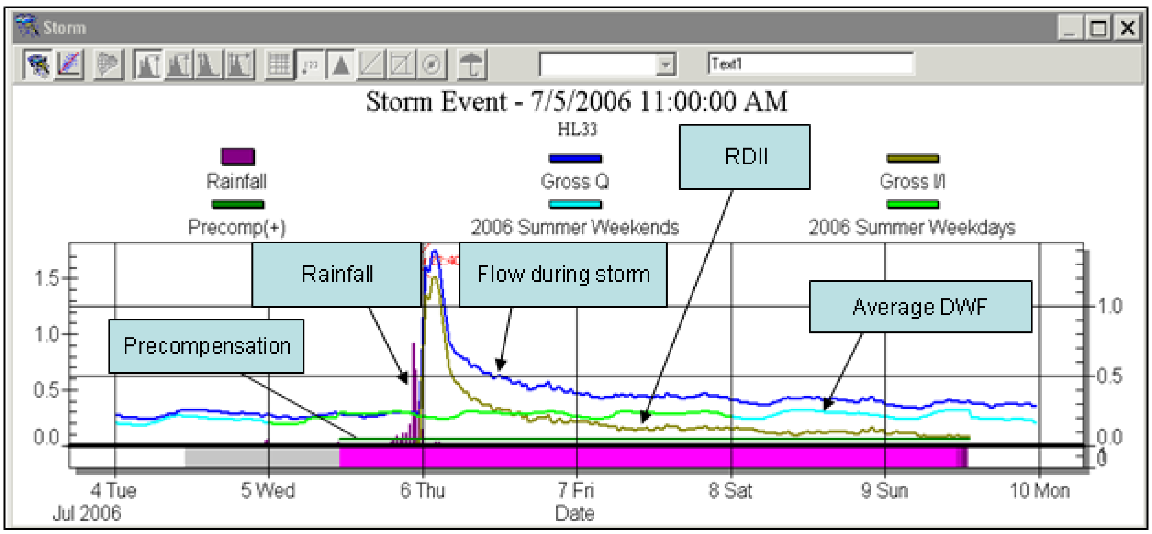


Figure 4-25. Wet weather components in Sli/icer to calculate RDII.

Once the storm calculations are performed, the user can generate a Q versus I plot which exhibits correlation between RDII responses and the corresponding rainfall amounts (Figure 4-26). The parameters necessary for calibrating the model for wet weather flow such as capture coefficient and depression storage can be obtained from these Q versus I plots in Sli/icer. This regression analysis is further explained in the Section 4.3.2.

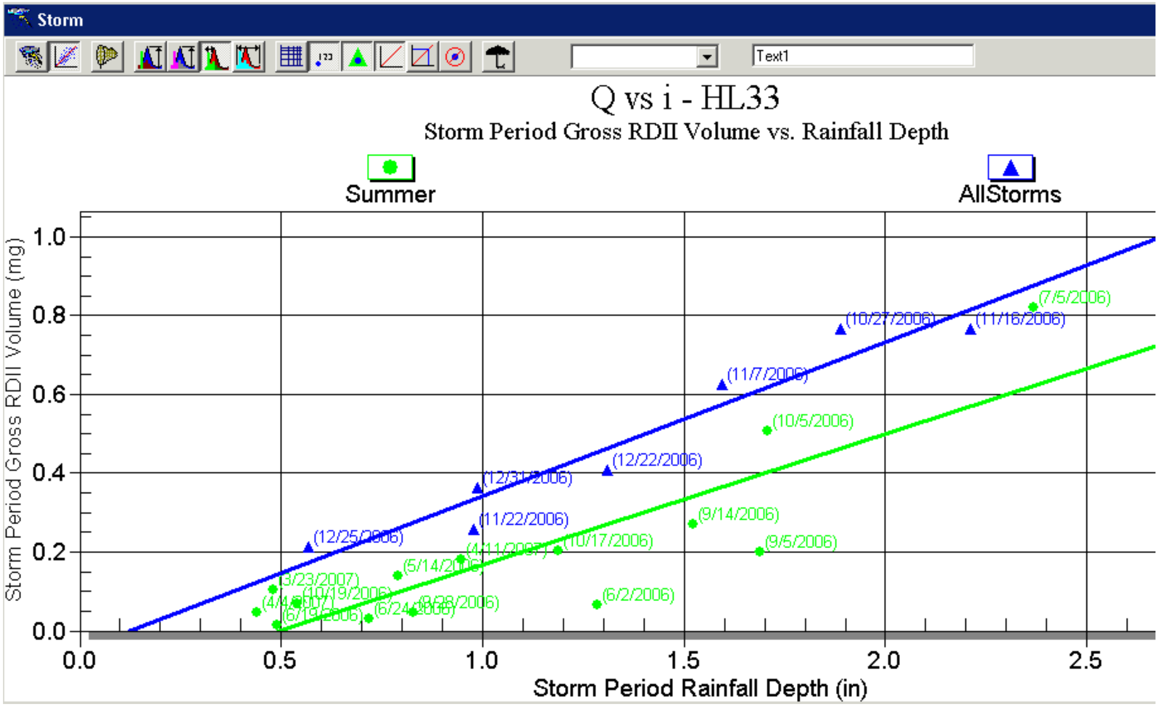


Figure 4-26. . Q vs. I Plot in Sli/icer

Graph Tab:

The graph tab allows a user to plot scattergraphs for each site that can help in understanding the hydraulic conditions during dry and wet weather periods. Figure 4-27 shows a Sli/icer scatter plot for HL16. The scatter graph shows that HL16 experienced sewer surcharging up to about 6 feet for several wet weather events including the July 5 storm. A small inverted siphon located directly downstream of HL16 probably acted as a flow restriction during wet weather events. Figure 4-28 shows a Sli/icer scatter plot for HL07, a flow meter very close to the downstream end of the HLI. The 100" diameter pipe had an accumulated 32" of sediment depth. The scattergraph shows there were several SSO events at or near this location because the surcharge depth exceeded the manhole depth of 136" for several events including the July 5th and November 16th storms. The cluster of blue dots implies that flow depth is from half to almost full pipe diameter even during dry days. Sli/icer has options to color-code time intervals of storms to investigate any occurrence of overflows. The behavior of the scattergraphs enables the HLSS team to predict whether the overflow occurred upstream or downstream of the flow monitor.

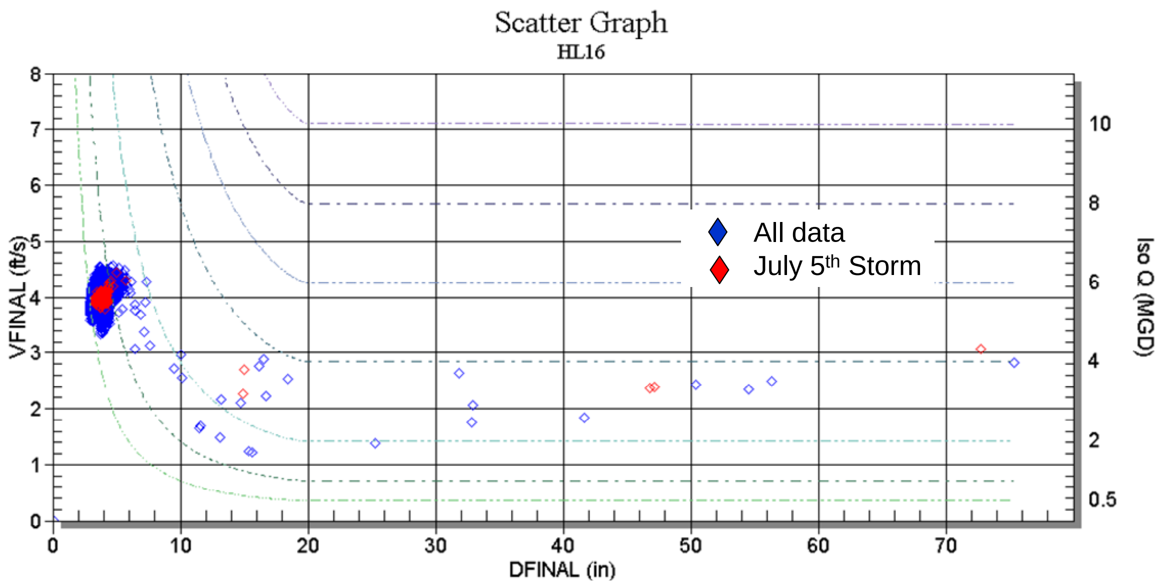


Figure 4-27. Scattergraph at HL16 with surcharges

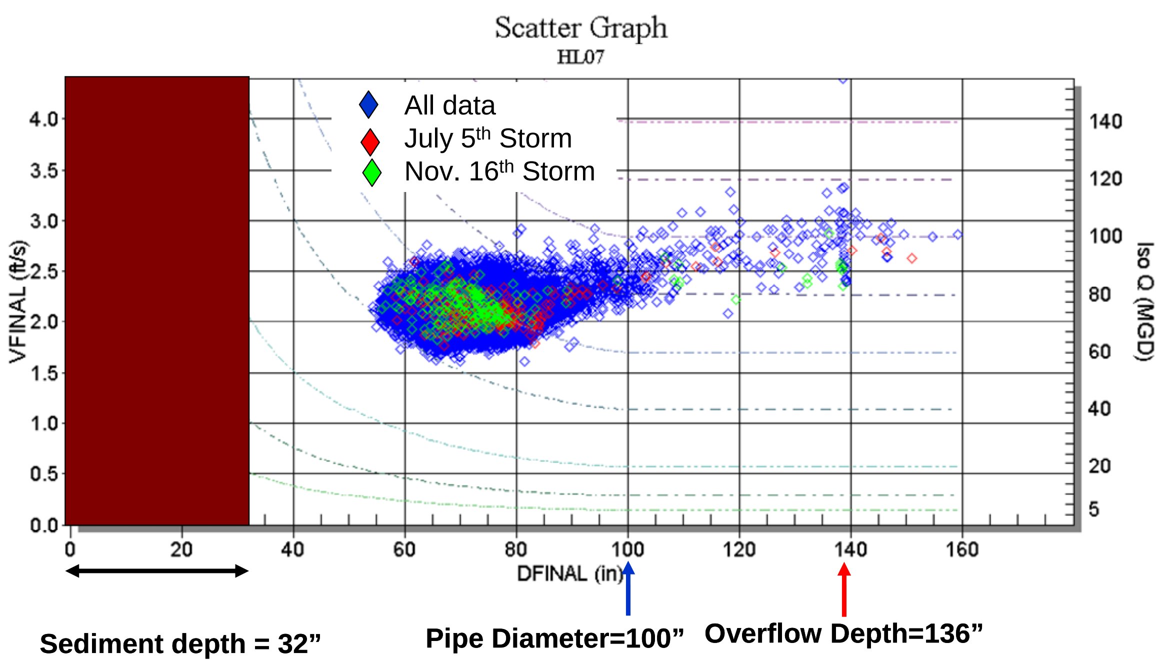


Figure 4-28. Scattergraph at HL07 with SSO events

4.3.2 Dry Weather Flow Components

The individual DWF components and their derivation for the various flow meters within the HLSS are described in this section.

Groundwater Base Infiltration:

Groundwater can seep into sewers through defective pipes, loose pipe joints, or cracks in manhole chambers even during dry days. This groundwater infiltration rate, also known as base infiltration (BI), can vary seasonally with higher rates during fall and winter periods when there is high groundwater level and soil moisture, and lower during the summer and extended dry periods.

The BI is estimated from the Sli/icer processed DWF data (i.e., daily average flow and diurnal pattern). There are four empirical methods available in Sli/icer to disaggregate BI from the total DWF:

- Average Daily Flow - (Average - Minimum)/Factor Method
- Minimum Daily Flow * Factor Method
- Average Daily Flow * Factor Method
- Stevens/Schutzbach (SS) Method

For HLSS, the modeling team used the SS method for calculating BI based on recommendations from 1015 and Sli/icer developers at ADS. The SS empirical equation for calculating BI is:

$$BI = \frac{0.4\,MDF}{1 - 0.6\left(MDF/ADF\right)^{ADF^{0.7}}}$$

where, ADF is the Average Daily Flow rate and MDF is the Minimum Daily Flow rate.

In comparison to the other three methods, the SS method provides good estimates of BI for small as well as large flow basins. The SS equation uses curve fitting technique to increase the reliability of BI estimation at flow metering locations with very low or very high flows (Mitchell et al., 2007). Figure 4-29 shows the dry day table available in Sli/icer, produced with the SS method.

The total DWF can be decomposed into BI and the wastewater production (WWP) for each flow basin as:

$$\text{Net DWF} = \text{Net WWP} + \text{Net BI}$$

where, the Net DWF is the average flow rate for each day group (e.g., Summer 06 weekday), Net WWP is the discrete wastewater production, and Net BI represents base infiltration.

All four methods for estimating BI are based on standard patterns generated by typical residential areas of sub-division size. The presence of industrial or commercial flows or patterns from large pumping station will cause these estimates to 'miss the mark'. Also larger flows with the dampening affect of travel time will interfere with BI estimates. The result is that in large sewer systems there are enough of these interferences to prevent the application of typical flow balancing techniques. Typical flow balancing techniques can result in apparent high BI or even negative BI. Consequently, these BI and WWP values cannot be directly used for model calibration. The data from the Sli/icer dry day table shown in Figure 4-29 was exported for analyses and checked for any data inconsistencies. Although Sli/icer provided two separate BI values for the weekday and weekend patterns, the HLSS team developed weighted averages from these two values as shown below:

BI = 5/7*Weekday NET BI + 2/7*Weekend NetBI

Waste Water Production (WWP):

The WWP is the portion of total DWF that represents only the residential wastewater contributions. The WWP amount can be calculated by subtracting BI from the total DWF.

In Sli/icer, wastewater per length (WW/L) is another parameter available to define the wastewater component in a basin. The value of WW/L can be used to judge if the DWF rate and its decomposition are reasonable. A reasonable range for WW/L is 2 to 7 gal/LF/day for residential areas and 5 to 20 (gal/ft/day) for high-density housing and commercial areas. The WW/L was used as a QA/QC metric during DWF processing.

Water per Capita Usage:

The WWP must be converted to per capita water usage in order to be used as an input for InfoWorks. The per capita number is derived from WWP and total population of a flow basin derived from the 2000 census data. Normally, the values from residential areas vary between 30 to 150 GPD. When the per capita rates are out of the normal range, it usually indicates mixed land uses such as industrial, institutional or commercial dischargers whose wastewater flows are not population dependent.

Diurnal Variations in Dry Weather Flow:

Wastewater discharges from residential areas vary over the course of a day (24–hour cycle) depending on water usage. These flows are inherently unsteady due to the varying yet continuous discharges from different land uses. In order to capture this effectively for comparison of modeled and monitored flows, diurnal variations are explicitly included in the model. The water usage during weekdays distinctly differs from weekends as seen in Figure 4-30.

Gr	Nt	Tr	Bl	Year	Season	DayGroup	Num	Alt	AltYear	AltSeason	AltDayGroup	TrPkDate	TracePk	GrossPeak	GrossMin	GrossAvg	NetPeak	NetMin	NetAvg	GroWWP	GroBlnfil	NetWWP	NetBlnfil	WW/L	WWMethod	Factor(%)
				2006	Summer	Weekdays	58		2006	Summer	Weekdays	05/09/2006	0.986	0.816	0.415	0.643	0.035	0.000	0.002	0.348	0.295	0.043	-0.091	1.498	Stevens/S	88
				2006	Summer	Weekends	21		2006	Summer	Weekends	09/24/2006	1.461	0.827	0.420	0.673	0.000	0.000	0.000	0.384	0.289	0.019	-0.086	0.673	Stevens/S	88
				2007	Winter	Weekdays	43		2007	Winter	Weekdays	02/09/2007	1.064	0.850	0.584	0.735	0.124	0.031	0.063	0.270	0.465	0.036	0.028	1.260	Stevens/S	88
				2007	Winter	Weekends	20		2007	Winter	Weekends	01/14/2007	1.040	0.895	0.592	0.765	0.110	0.038	0.076	0.306	0.460	0.059	0.017	2.085	Stevens/S	88
				2007	Summer	Weekdays	23		2007	Summer	Weekdays	03/28/2007	1.042	0.915	0.638	0.798	0.187	0.127	0.154	0.293	0.506	0.043	0.112	1.511	Stevens/S	88
				2007	Summer	Weekends	7		2007	Summer	Weekends	03/11/2007	1.162	0.993	0.654	0.856	0.183	0.066	0.121	0.362	0.494	0.096	0.025	3.395	Stevens/S	88

Figure 4-29. ***Dry Day table display from Sli/icer***

The patterns are also different for commercial and residential users. This is evident at flow basins that are influenced by discharges from the Ashburton WFP (e.g., HL28, HL26 and HL25). The diurnal pattern of these flow basins is highly influenced by the wastewater discharges from this plant.

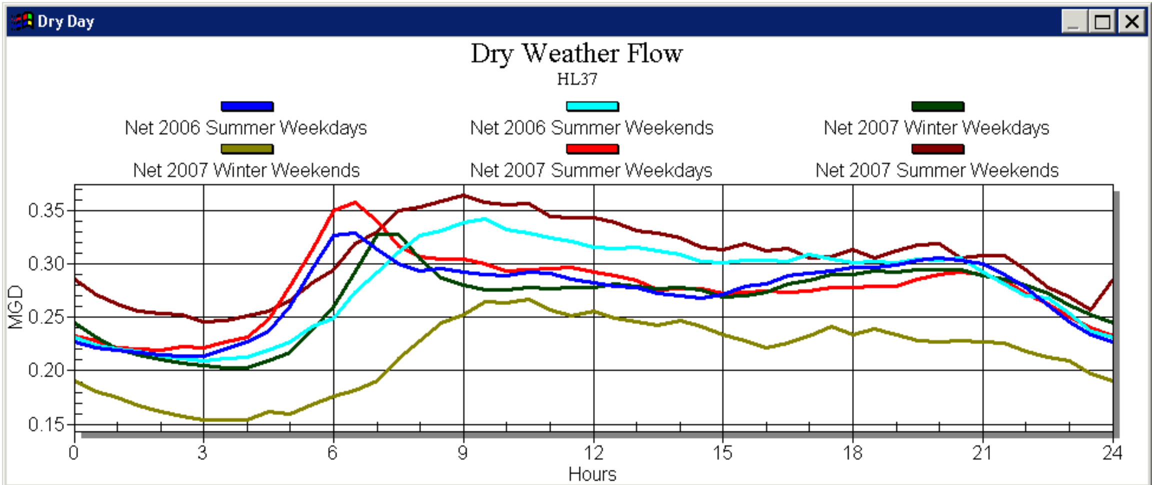


Figure 4-30. Weekday and Weekend average diurnal pattern for Summer 2006, Winter 2007 and Summer2007 for HL37.

When the diurnal patterns were plotted with dry day values for a specific day group, some prominent outliers were eliminated from the DWF analysis. Diurnal patterns for the three seasons were exported in a model-compatible format for processing and analysis. The BI amount was subtracted from the diurnal pattern of DWF to obtain the diurnal pattern of WWP as hydraulic model input.

4.3.3 RDII – Rainfall Dependent Inflow/Infiltration

RDII represents the flow above the normal DWF pattern in a sewer system, and is the additional flow response in sewers during and subsequent to a rainy period. The wet weather flows can dominate dry weather flows due to the presence of high RDII as shown in Figure 4-25. The RDII portion of flow for all storm events can be analyzed using Sli/icer.

Sli/icer estimates the RDII volume for each storm event by subtracting the average DWF from the total measured flow response. Once the storm calculations are performed for each site, Sli/icer generates flow (Q) versus rainfall (I) graphs. Figure 4-31 shows the correlation between RDII volumes and rainfall depths for all storm events in HL39. In some cases, one or two storm events (outliers) can distort these graphs. These outliers are identified and eliminated from the analysis. Although Sli/icer provides the user with the option of gross or net Q versus I, the gross Q was chosen by the HLSS team to resolve flow imbalance issues described in Section 4.4.2. The capture coefficient and depression storage, two important parameters necessary for wet weather calibration, were obtained from a regression analysis of the Q versus I graphs for each sub-basin.

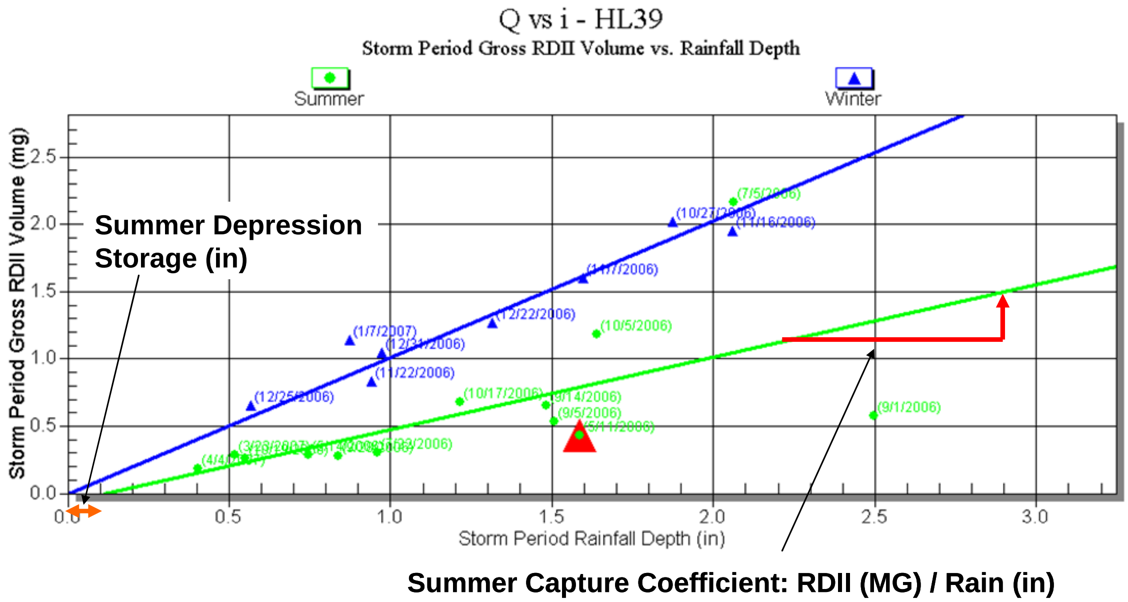


Figure 4-31. RDII volume vs. Rainfall depth for HL39

A capture coefficient is the fraction of total rainfall that enters a sewer system as RDII during storm events. A depression storage is the volume of rain that must fall before a wet weather runoff can occur, i.e., the surface depressions that need to be filled prior to initiating overland flow in an urban hydrology context. The Q versus I graphs help to evaluate the performance of a sewershed and rank sewersheds based on the RDII severities for further rehabilitation efforts.

Since the capture coefficient and depression storage can vary significantly in different seasons, the 29 global storms in Sli/icer were separated into summer and winter storms for the RDII analysis shown in Figure 4-32. This enabled the modeling team to derive the appropriate seasonal capture coefficients.

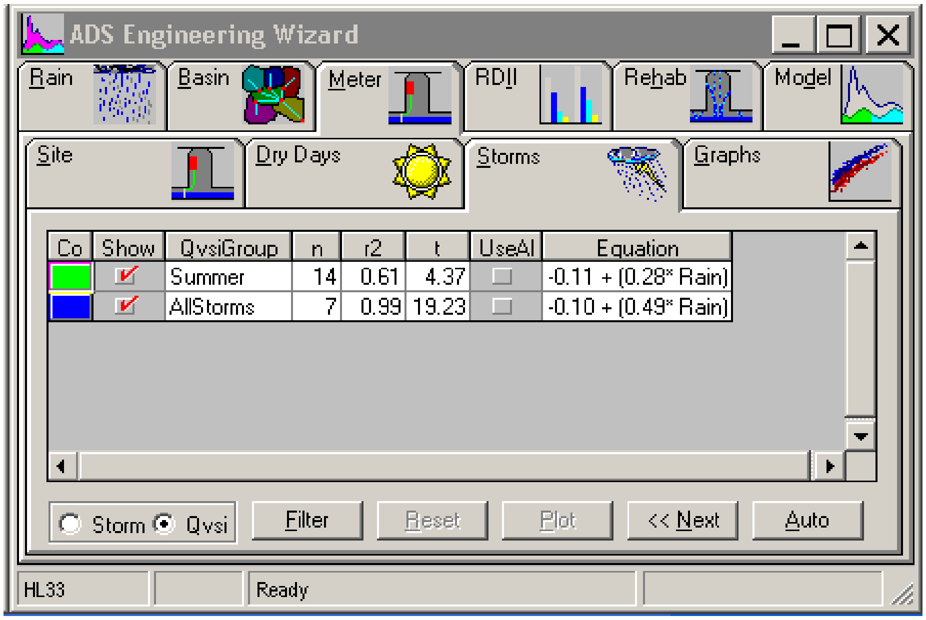


Figure 4-32. Seasonal capture coefficient in Sli/icer from Q vs. I analysis.

4.3.4 Ashburton Water Filtration Plant Discharges

The Ashburton WFP, located near the GRI, is a major drinking water treatment plant owned by the City (see Figure 4-33). This plant discharges its wastewater from the sedimentation basin (Sed-Basin) and filter backwash water into the GRI. This is the most significant point discharge. The discharge rate to GRI can be up to 10 MGD due to the use of temporary pump stations located at the Washwater Lake, which is currently under rehabilitation. This section summarizes the discharges to the GRI under existing system conditions.

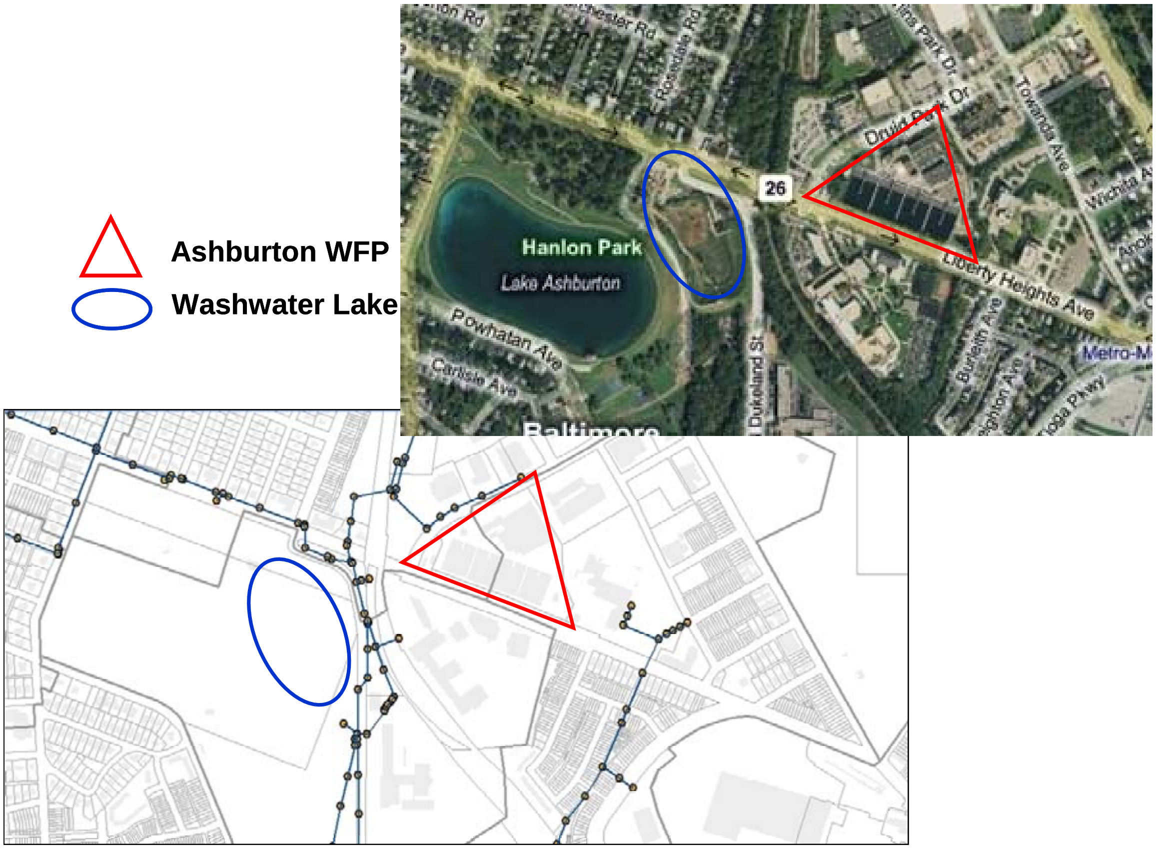


Figure 4-33. Ashburton Water Filtration Plant in HLSS

Sedimentation Basin Discharge:

There are four sedimentation basins in the plant and three are currently in operation (see Figure 4-34). The plant operates the sediment cleaning process (blow-off) every hour from one of the operating basins. This discharge with high levels of sediment concentration flows by gravity directly to the GRI.

The sedimentation basins drain to the GRI at a location directly upstream of the HL31 flow meter. The periodic and constant discharge pattern can easily be seen from the flow data at HL31. Figure 4-35 shows the reproduced Sed-Basin discharge on a dry day along with the observed flow at HL31. The reproduced HL31 flow was created as the sum of base GRI flow and reproduced Sed-Basin discharge. The estimated discharge of the Sed-Basin is approximately 22,000 gallons and the peak discharge rate is approximately 1 MGD.

Figure 4-34. Sedimentation Basin in Ashburton WFP

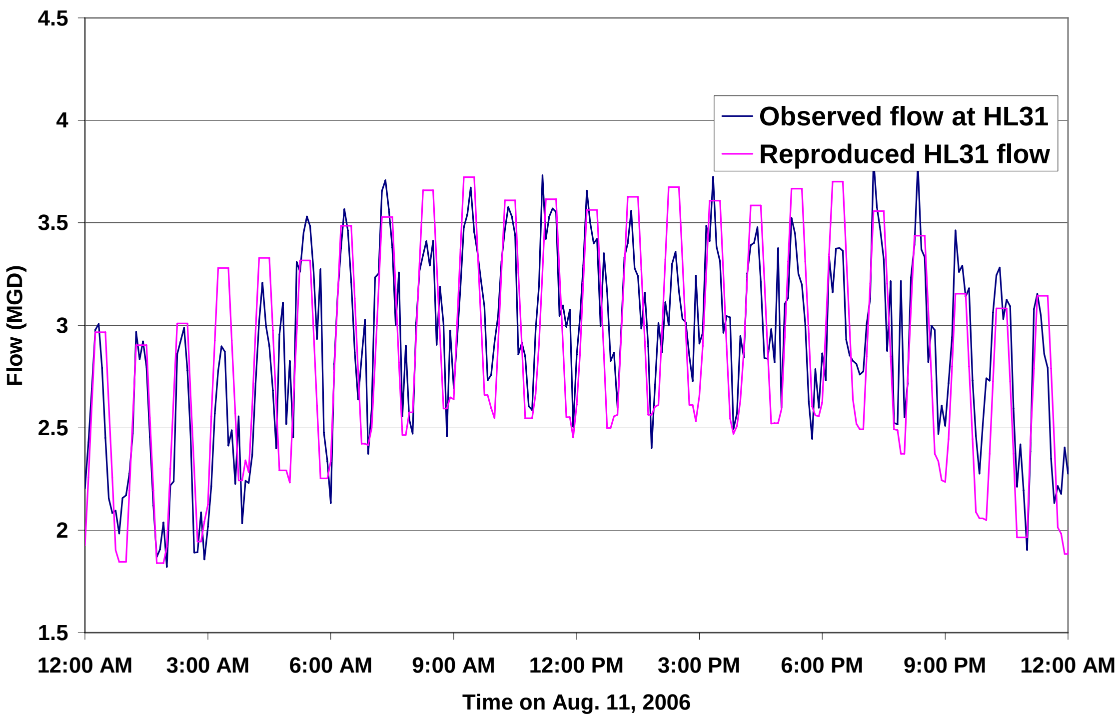


Figure 4-35. Reproduced Sed-Basin Discharge Pattern

Filter Backwash Discharge:

The plant discharges its filter backwash water to the Washwater Lake, which in turn discharges to the GRI. This discharge has lower sediment concentrations than the Sed-Basin discharge. The lake is currently under rehabilitation. At present, the filter backwash discharge goes directly to a gabion structure in the lake (Figure 4-36) and the water is then pumped out to GRI. Since the lake needs to be kept dry during construction, additional pumps have been installed to dewater the lake during rainy periods. The filter backwash discharges to GRI are neither constant nor periodic because multiple pumps are in operation.

For calibration purposes, the HLSS team extracted data from the downstream flow meters (e.g., HL28 and HL26) to provide time series inflows for the model. The HLSS team initially attempted to model the pump sequencing to create discharges equivalent to those seen in the flow data. This turned out to be a cumbersome and complicated effort. In addition, these pumps will be eliminated after lake rehabilitation is complete. Based on the rehabilitation plan, the filter backwash water from the plant will discharge to the lake, which in turn will discharge into GRI through automated controls or manually operated valves. Because of this the modeling team used an external time-series approach rather than the current pump sequencing.

The WFP discharge was further studied based on data from the new flow meter, HL812B, which had in operation since April 8^{th} 2008. The flow meter was installed directly on the discharge pipe from the lake. Figure 4-37 shows the measured total discharge rate (at 15-minute intervals) for September 5-8, 2008. During this period, a total of approximately 1.6” of rainfall occurred on September 6 during Hurricane Hanna. The hydrograph showed a discharge of up to 10 MGD, but there was no significant difference in discharge pattern between the dry days and storm day (September 6).

Figure 4-36. Gabion structure in the Washwater Lake

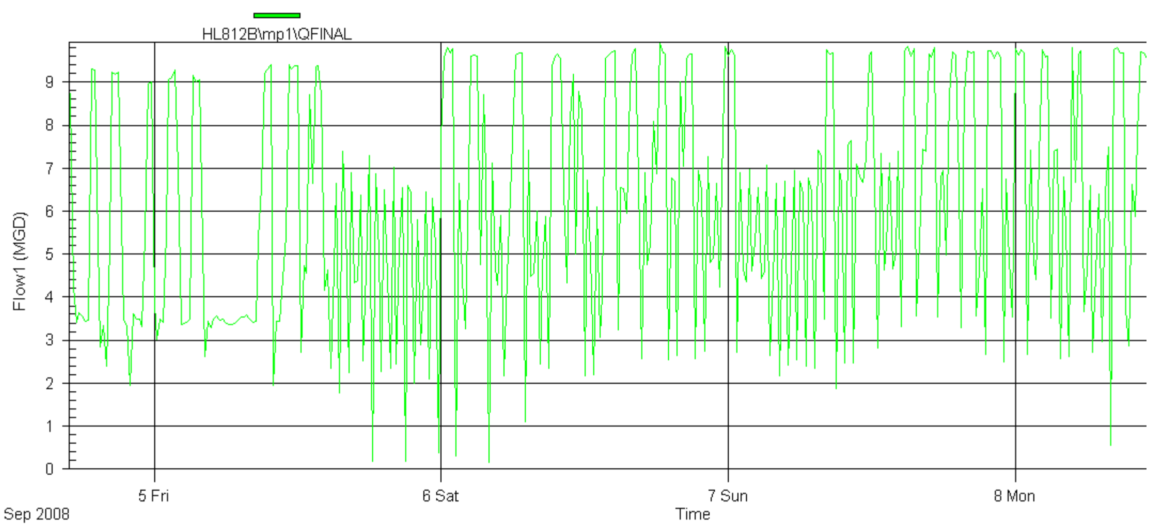


Figure 4-37. Discharge from Washwater Lake for the period of September 5-8, 2008

Data Sources and Site Visits:

The HLSS team had very limited initial information about the plant discharges. The team conducted several site visits to the Ashburton WFP to interview the plant operators in order to understand the discharge patterns and locations. Several copies of the discharge records and contract drawings were provided by the plant staff. A list of the site visits and obtained records is provided below.

- Plant visits:
  - 1st visit on 4/1/08: Discussion with an operator
  - 2nd visit on 4/23/08: Checked out drawings to make copies
  - 3rd visit on 6/5/08: Obtained V-Drain discharge

- Records:
  - Report "Ashburton Sludge Separation Facility" – overview of Ashburton discharges
  - Contract drawing 1143 "Washwater Lake Rehabilitation"
  - Contract drawing 1040 "Ashburton Filtration Plant"
  - Circular charts: V-drain Discharge from WFP (6/24/06 – 5/10/07)
  - Circular charts: Discharge from Washwater Lake (12/15/05 – 7/30/07, 12/22/07 – 5/19/08 with some missing records)

Figure 4-38 shows an example circular chart with Washwater Lake discharges. Approximate discharge range and frequency were extracted from these charts to represent the discharges appropriately in the model.

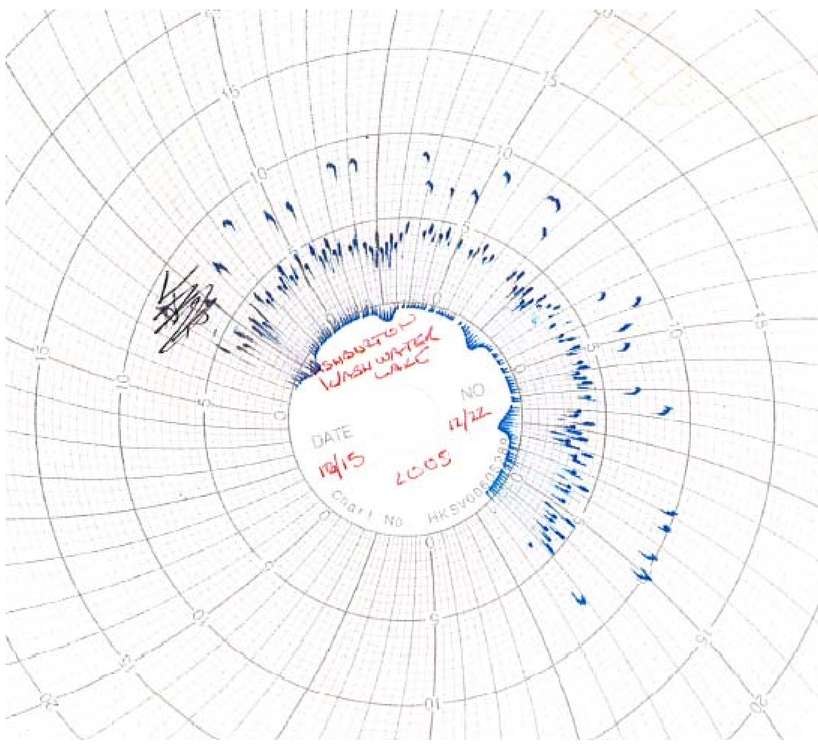


Figure 4-38. Circular chart showing discharge from Washwater Lake pumps from December 15-22, 2005.

4.4 FLOW BALANCE ANALYSIS

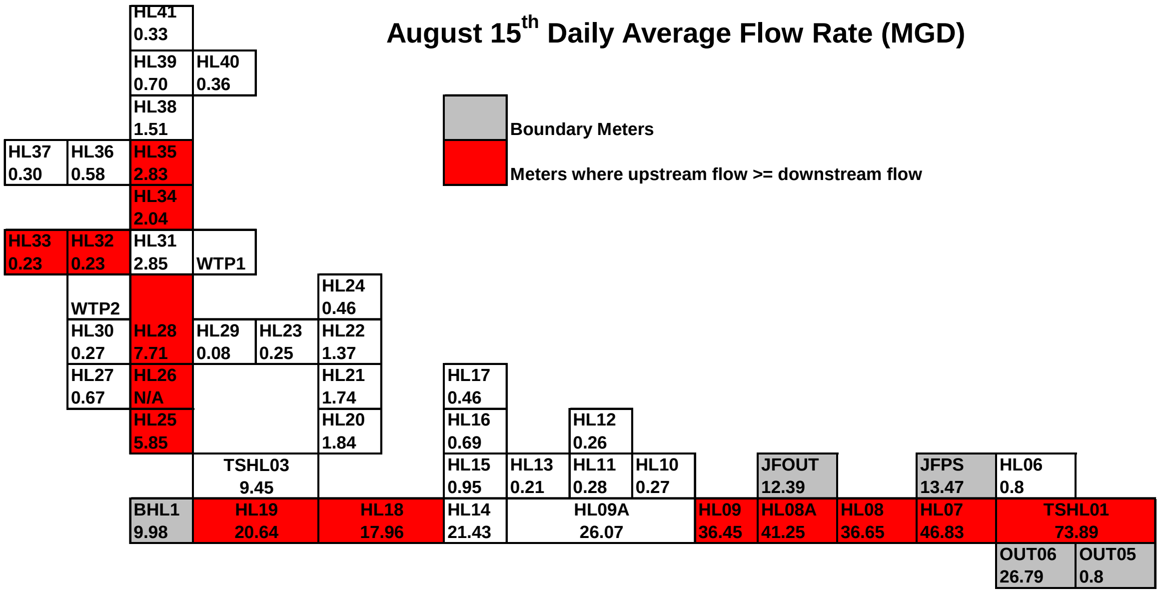
As part of the hydraulic model development, the DWF parameters (e.g., WWP per capita and diurnal pattern) and RDII parameters (e.g., capture coefficient and depression storage) need to be determined for each flow basin. For most upstream basins, these parameters can be calculated entirely based on flow data from the basin. However, the process becomes more complicated for meters that receive contributions from several upstream basins. The total flow at a downstream meter may not add up to the flows measured at the individual upstream meters. There is a flow balance issue that presents difficulties in determining DWF or RDII contributions of these basins. A comprehensive, system-wide analysis is needed to determine whether the flow imbalance occurs due to flow data quality issues or real conditions (e.g., SSOs or exfiltration of flow). This flow balancing process involves making certain assumptions or creating empirical relationships to resolve differences and proceed with the development of model parameters. The approaches used for DWF and RDII are discussed separately in the following sections.

4.4.1 Dry Weather Flow

Flow Balance in HLSS

A major example of flow imbalance is where the upstream flow rate is higher than the downstream rate. This condition could occur if there is exfiltration of flows from sewers through pipe defects such as cracks and holes, or due to measurement errors that result from local hydraulic conditions or faulty flow meters. For example, if the local hydraulic conditions skewed the velocity measurements, this would cause a flow imbalance. Therefore, a system-wide flow data analysis was conducted to identify flow imbalances. Based on field knowledge of the HLSS system, the modeling team determined that the flow imbalance primarily resulted from flow measurement errors.

Figure 4-39 shows the daily average DWF on August 15 and December 7, 2006 in various basins of HLSS. The basins where flow rate at an upstream location is higher than the downstream location are highlighted in red. In most cases, the flow balance issues were seen at the downstream HLI metering locations. The local net flow for each HLI downstream flow basin (e.g., HL09 and HL08) is less than 1 MGD, which is only a small fraction of the total flow at downstream HLI which is over 30 MGD at HL09. The flow rate monitoring accuracy is +/- 10%, which gives an accuracy tolerance of +/- 3MGD for flow rates at downstream HLI flow meters. This tolerance is much larger than the local net flow from downstream HLI basins. This is a primary reason for the HLSS team's conclusion that the flow monitoring errors significantly affected the characterization of net flow contributions from many downstream HLI basins.



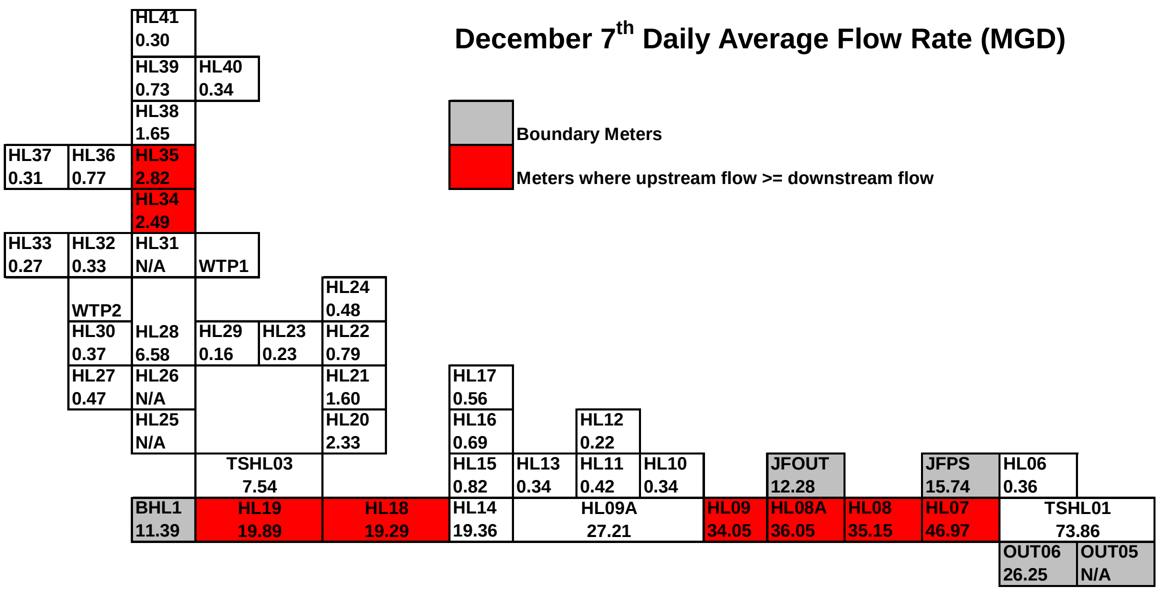


Figure 4-39. Dry weather flow propagation in HLSS and meters with flow imbalance on August 15th (above) and December 7th (below)

Flow Data Quality Assessment

As described in Section 4.3.3, the ratio between WWP and BI can be calculated using Sli/icer. The values for WWP per capita from each basin were used to assess if each flow meter provided accurate enough data to compute the net flow contributions. WWP per capita values were also utilized to segregate WWP and BI components of flow. A flow meter was deemed to be "good" if the calculated per capita value was between 30 and 150 gallon per day per capita (gpcd) and deemed to be "bad" if the WWP per capita was outside of this range. This range is larger than the typical 45 – 90 gpcd for residential landuses. The larger range accounts for localized increases or decreases based on the mix of other commercial and industrial land uses (e.g., local schools, commercial offices, and factories).

As shown in Figure 4-40, the upstream meters were primarily "good" in terms of data quality. For these meters, the per capita consumption versus the total DWF and the ratio of WWP to BI were calculated in order to adjust the data from "bad" meters according to the procedure outlined below.

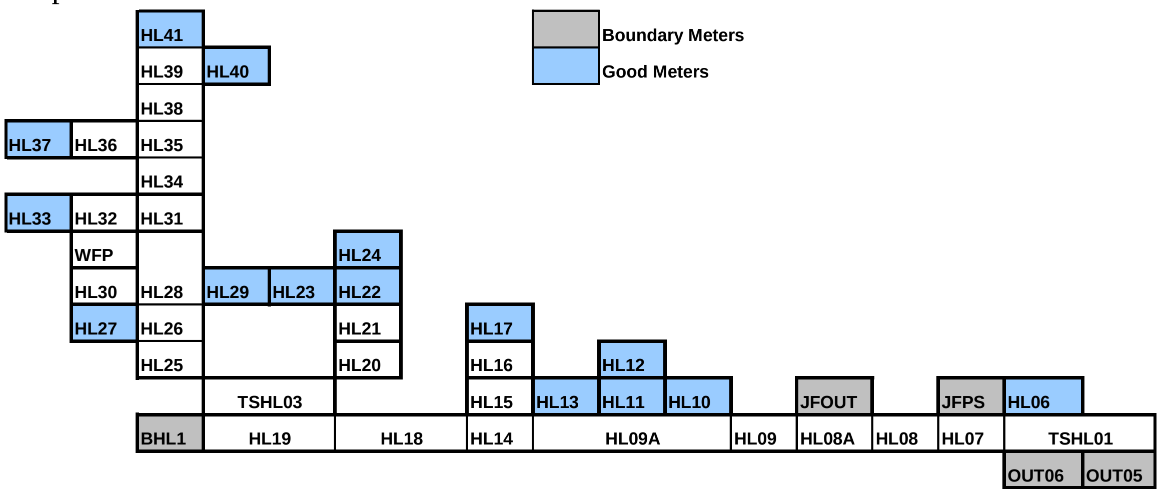


Figure 4-40. Good flow meters in HLSS where total DWF rate and BI/WWP decomposition in Sli/icer are both reasonable.

1) Water consumption versus WWP

Water consumption data for winter 2006, 2007, and 2008 were provided by the City for each flow basin in HLSS. Since the winter 2007 timeframe was within the primary flow monitoring period for HLSS, the winter 2007 data was compared with Sli/icer calculated net WWP for the good meters. Then, the following simple empirical relationship was developed to determine the WWP contribution from water consumption data:

WWP = 0.87 * total water consumption in the contributing basin

2) WWP versus BI

In a similar manner, the following average WWP to BI ratios for HLSS were calculated from the ratios obtained from good meter data for each season within the primary flow monitoring period:

WWP = 0.42 * total DWF for Summer 06

WWP = 0.39 * total DWF for Winter 07

WWP = 0.40 * total DWF for Summer 07

DWF Parameter Assessment for Bad Meters

Using the empirical relationships shown above, the DWF parameters for each bad meter were determined as described below. The procedure for calculation of DWF is also depicted in Figure 4-41.

1. Flow meter basins were aggregated only if the flow data at intermediate basins were considered inaccurate, which was applicable for HL15-HL16, HL20-HL21, and HL38-HL39 depending on the season;
2. For flow basins which were neither aggregated nor on the HLI, the total DWF was considered accurate. The average WWP to BI ratio was applied to decompose the total DWF into WWP and BI components; and
3. For flow basins which were not aggregated, but are on the HLI, the water consumption to DWF discharge ratio was used to calculate the total DWF. The average WWP to BI ratio was then used to decompose total DWF into the WWP and BI components. The BI was further adjusted during the process of model calibration to improve the correlation between monitored and modeled data at good metering locations.

DWF Parameters for the Hydraulic Model

Based on the assessment above, interceptor meters were categorized into calibration meters and faulty meters. Figures 4-42, 4-43, and 4-44 show the DWF calibration meters and their corresponding DWF parameters for the Summer 06, Winter 07, and Summer 07 time periods, respectively. The DWF decomposition column specifies whether the WWP value came from Sli/icer or water consumption data.

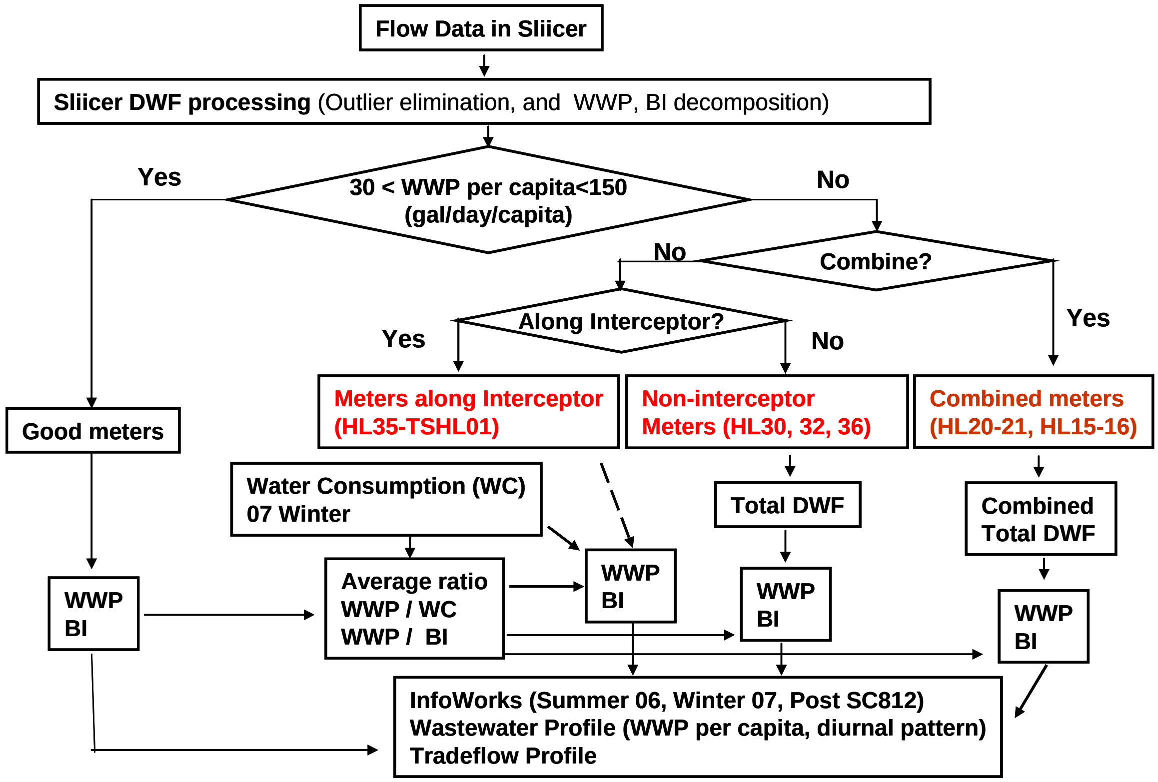
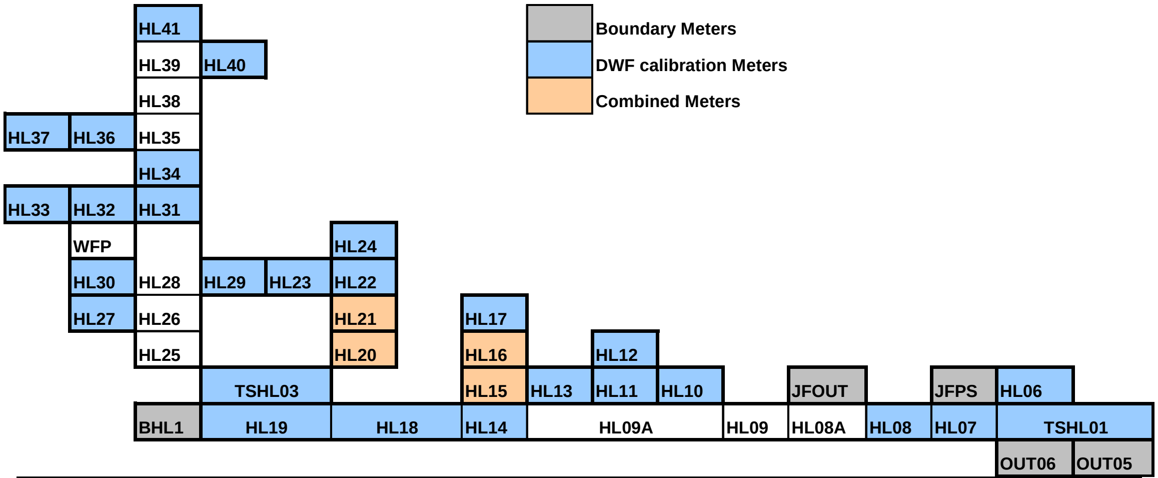
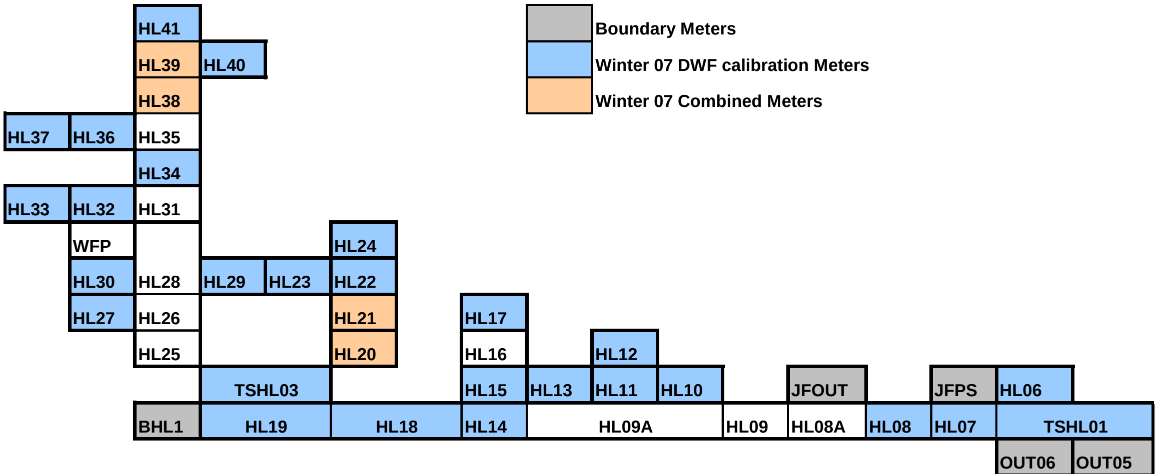


Figure 4-41. Process for Calculating DWF Parameters.



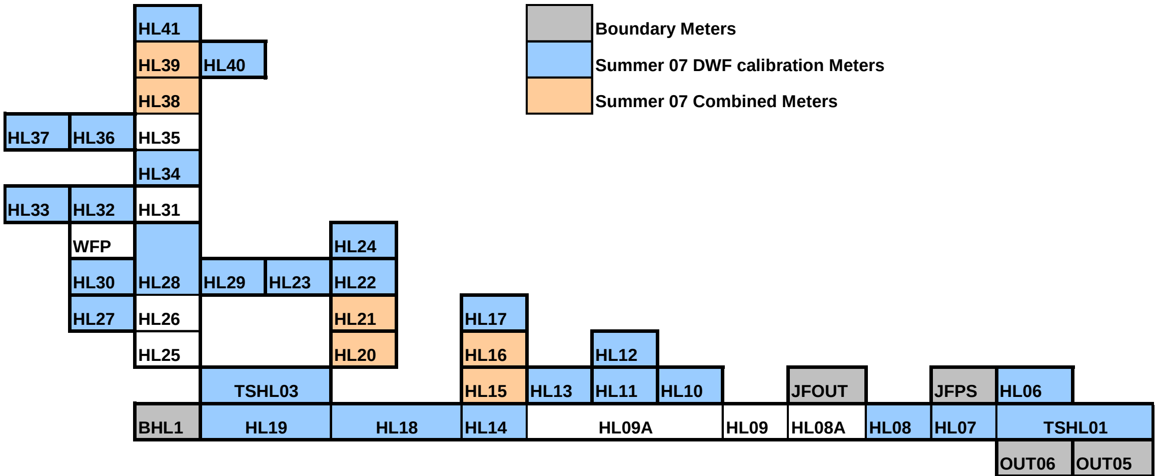
Flow Basin	For Calibration?	DWF decomposition	Population	Summer 2006 WWP-weekday (gal/day/capita)	WWP-weekend (gal/day/capita)	WWP (MGD)	BI (MGD)	Total (MGD)	BI/ Total DWF (%)
HL06	Yes	Sli/icer	2957	52.5	66.7	0.17	0.64	0.81	79.4
HL07	Yes	Water Consumption	2197	55.7	55.0	0.12	0.17	0.29	58.0
HL08	Yes	Water Consumption	2535	64.3	63.6	0.16	0.22	0.39	58.0
HL08A	No	Water Consumption	667	64.3	63.6	0.04	0.06	0.10	58.0
HL09	No	Water Consumption	3558	126.1	124.6	0.45	0.62	1.06	58.0
HL09A	No	Water Consumption	111	126.1	124.6	0.01	0.02	0.03	58.0
HL10	Yes	Sli/icer	2047	116.4	96.4	0.23	0.20	0.42	46.3
HL11	Yes	Sli/icer	1028	143.4	91.8	0.13	0.10	0.24	44.0
HL12	Yes	Sli/icer	3093	37.1	41.9	0.12	0.14	0.26	53.9
HL13	Yes	Sli/icer	1966	42.2	41.7	0.08	0.14	0.23	63.5
HL14	Yes	Water Consumption	2661	53.6	53.0	0.14	0.20	0.34	58.0
HL15	Combined	Sli/icer	2135	34.8	29.5	0.07	0.16	0.23	68.7
HL16	Combined	Sli/icer	3263	34.8	29.5	0.11	0.23	0.34	68.3
HL17	Yes	Sli/icer	2894	63.6	71.8	0.19	0.25	0.44	56.2
HL18	Yes	Water Consumption	3742	62.7	61.9	0.23	0.32	0.56	58.0
HL19	Yes	Water Consumption	1725	70.9	70.1	0.12	0.17	0.29	58.0
HL20	Combined	Sli/icer	3606	77.0	65.3	0.27	0.12	0.39	31.3
HL21	Combined	Sli/icer	3550	77.0	65.3	0.26	0.15	0.41	35.8
HL22	Yes	Sli/icer	3941	41.9	48.0	0.17	0.14	0.31	44.7
HL23	Yes	Sli/icer	3329	40.2	44.1	0.14	0.12	0.26	47.0
HL24	Yes	Sli/icer	4670	43.5	44.6	0.20	0.26	0.46	55.6
HL25	No	Water Consumption	5199	58.8	58.1	0.30	0.42	0.73	58.0
HL26	No	Water Consumption	4382	69.8	69.0	0.30	0.42	0.73	58.0
HL27	Yes	Sli/icer	4132	69.3	69.7	0.29	0.37	0.66	56.4
HL28	No	Water Consumption	2289	66.8	66.0	0.15	0.21	0.36	58.0
HL29	Yes	Sli/icer	1461	39.4	36.7	0.06	0.06	0.12	51.1
HL30	Yes	Water Consumption	3354	56.6	55.9	0.19	0.14	0.33	42.5
HL31	Yes	Water Consumption	1502	50.0	50.0	0.08	0.01	0.09	11.8
HL32	Yes	Water Consumption	1641	50.0	50.0	0.08	0.01	0.10	14.6
HL33	Yes	Sli/icer	1908	31.7	32.7	0.06	0.17	0.23	73.0
HL34	Yes	Water Consumption	1963	57.1	56.5	0.11	0.01	0.12	10.0
HL35	No	Water Consumption	3594	56.7	56.1	0.20	0.02	0.23	10.0
HL36	Yes	Water Consumption	1109	64.3	63.6	0.07	0.26	0.33	78.5
HL37	Yes	Sli/icer	3094	40.8	43.4	0.13	0.15	0.28	53.4
HL38	No	Water Consumption	2294	71.1	70.3	0.16	0.02	0.18	10.0
HL39	No	Water Consumption	3468	47.0	46.5	0.16	0.02	0.18	10.0
HL40	Yes	Sli/icer	2754	52.2	58.4	0.15	0.20	0.35	57.8
HL41	Yes	Sli/icer	2007	82.3	98.2	0.17	0.18	0.35	50.5
TSHL01	Yes	Water Consumption	67	55.7	55.0	0.00	0.01	0.01	58.0
TSHL03	Yes	Water Consumption	877	93.0	91.9	0.08	0.11	0.19	58.0

Figure 4-42. Summer 06 HLSS calibration meters (above) and processed DWF parameters for model use (below)



Flow Basin	For Calibration?	DWF decomposition	Population	Winter 2007 WWP-weekday (gal/day/capita)	WWP-weekend (gal/day/capita)	WWP (MGD)	BI (MGD)	Total (MGD)	BI/Total DWF (%)
HL06	Yes	Sli/icer	2957	41.9	44.3	0.13	0.31	0.43	70.8
HL07	Yes	Water Consumption	2197	46.8	49.6	0.10	0.16	0.27	61.0
HL08	Yes	Water Consumption	2535	54.1	57.3	0.14	0.22	0.36	61.0
HL08A	No	Water Consumption	667	54.1	57.3	0.04	0.06	0.09	61.0
HL09	No	Water Consumption	3558	106.0	112.2	0.38	0.60	0.98	61.0
HL09A	No	Water Consumption	111	106.0	112.2	0.01	0.02	0.03	61.0
HL10	Yes	Sli/icer	2047	57.4	62.3	0.12	0.21	0.33	64.0
HL11	Yes	Sli/icer	1028	86.7	90.6	0.09	0.10	0.19	51.7
HL12	Yes	Sli/icer	3093	38.8	38.2	0.12	0.15	0.27	55.0
HL13	Yes	Sli/icer	1966	48.9	53.5	0.10	0.25	0.35	71.5
HL14	Yes	Water Consumption	2661	45.1	47.7	0.12	0.19	0.31	61.0
HL15	Yes	Water Consumption	2135	74.3	78.6	0.16	0.01	0.18	8.0
HL16	No	Water Consumption	3263	40.6	43.0	0.13	0.02	0.16	13.5
HL17	Yes	Sli/icer	2894	80.7	85.6	0.24	0.35	0.59	59.8
HL18	Yes	Water Consumption	3742	52.7	55.8	0.20	0.31	0.51	61.0
HL19	Yes	Water Consumption	1725	59.6	63.1	0.10	0.16	0.27	61.0
HL20	Combined	Sli/icer	3606	101.5	100.3	0.36	0.30	0.66	45.1
HL21	Combined	Sli/icer	3550	101.5	100.3	0.36	0.27	0.63	43.0
HL22	Yes	Sli/icer	3941	45.8	55.4	0.19	0.21	0.40	52.0
HL23	Yes	Sli/icer	3329	37.9	49.3	0.14	0.13	0.27	49.5
HL24	Yes	Sli/icer	4670	39.8	38.3	0.18	0.31	0.50	62.9
HL25	No	Water Consumption	5199	49.5	52.4	0.26	0.07	0.33	20.0
HL26	No	Water Consumption	4382	58.7	62.1	0.26	0.07	0.33	20.0
HL27	Yes	Sli/icer	4132	52.2	58.3	0.22	0.29	0.51	56.5
HL28	Yes	Water Consumption	2289	56.2	59.5	0.13	0.03	0.16	20.0
HL29	Yes	Sli/icer	1461	48.6	49.3	0.07	0.08	0.15	52.0
HL30	Yes	Water Consumption	3354	47.6	50.4	0.16	0.25	0.42	61.0
HL31	No	Water Consumption	1502	79.9	84.6	0.12	0.03	0.15	20.8
HL32	Yes	Water Consumption	1641	47.0	49.8	0.08	0.02	0.10	20.7
HL33	Yes	Sli/icer	1908	31.3	38.6	0.06	0.21	0.27	76.4
HL34	Yes	Water Consumption	1963	48.0	50.8	0.10	0.03	0.12	20.7
HL35	No	Water Consumption	3594	47.7	50.5	0.17	0.05	0.22	20.8
HL36	Yes	Water Consumption	1109	54.1	57.3	0.06	0.40	0.46	86.8
HL37	Yes	Sli/icer	3094	44.1	27.3	0.12	0.13	0.25	51.5
HL38	Combined	Sli/icer	2294	42.7	47.3	0.10	0.39	0.49	79.2
HL39	Combined	Sli/icer	3468	42.7	47.3	0.15	0.36	0.51	70.1
HL40	Yes	Sli/icer	2754	37.9	44.5	0.11	0.23	0.34	67.4
HL41	Yes	Sli/icer	2007	61.7	62.2	0.12	0.22	0.35	64.2
TSHL01	Yes	Water Consumption	67	46.8	49.6	0.00	0.00	0.01	61.0
TSHL03	Yes	Water Consumption	877	78.2	82.8	0.07	0.02	0.09	20.0

Figure 4-43. Winter 07 HLSS calibration meters (above) and processed DWF parameters for model use (below)



Flow Basin	For Calibration?	DWF decomposition	Population	Summer 2007 WWP-weekday (gal/day/capita)	WWP-weekend (gal/day/capita)	WWP (MGD)	BI (MGD)	Total (MGD)	BI/ Total DWF (%)
HL06	Yes	Sli/icer	2957	57.6	71.5	0.18	0.53	0.71	74.4
HL07	Yes	Water Consumption	2197	53.7	59.6	0.12	0.18	0.30	60.0
HL08	Yes	Water Consumption	2535	62.0	68.9	0.16	0.24	0.41	60.0
HL08A	No	Water Consumption	667	62.0	68.9	0.04	0.06	0.11	60.0
HL09	No	Water Consumption	3558	121.5	135.0	0.45	0.67	1.12	60.0
HL09A	No	Water Consumption	111	121.5	135.0	0.01	0.02	0.03	60.0
HL10	Yes	Sli/icer	2047	68.5	50.0	0.13	0.19	0.32	59.7
HL11	Yes	Sli/icer	1028	77.8	103.1	0.09	0.11	0.20	55.3
HL12	Yes	Sli/icer	3093	65.2	56.2	0.19	0.16	0.36	45.7
HL13	Yes	Sli/icer	1966	55.6	62.7	0.11	0.19	0.30	62.0
HL14	Yes	Water Consumption	2661	51.7	57.4	0.14	0.21	0.35	60.0
HL15	Combined	Sli/icer	2135	44.46	36.45	0.09	0.00	0.09	0.0
HL16	Combined	Sli/icer	3263	44.46	51.70	0.15	0.00	0.15	0.0
HL17	Yes	Sli/icer	2894	83.7	91.7	0.25	0.52	0.77	67.7
HL18	Yes	Water Consumption	3742	60.4	67.1	0.23	0.35	0.58	60.0
HL19	Yes	Water Consumption	1725	68.4	76.0	0.12	0.18	0.30	60.0
HL20	Combined	Sli/icer	3606	64.92	70.61	0.24	0.24	0.48	50.4
HL21	Combined	Sli/icer	3550	64.92	70.61	0.24	0.27	0.51	53.5
HL22	Yes	Sli/icer	3941	103.2	80.9	0.38	0.16	0.54	29.8
HL23	Yes	Sli/icer	3329	42.4	55.0	0.15	0.29	0.44	65.2
HL24	Yes	Sli/icer	4670	41.0	50.4	0.20	0.36	0.56	63.8
HL25	No	Water Consumption	5199	56.7	63.0	0.30	0.46	0.76	60.0
HL26	No	Water Consumption	4382	67.3	74.8	0.30	0.46	0.76	60.0
HL27	Yes	Sli/icer	4132	49.1	55.6	0.21	0.30	0.51	58.9
HL28	Yes	Water Consumption	2289	64.4	71.6	0.15	0.23	0.38	60.0
HL29	Yes	Sli/icer	1461	58.2	61.6	0.09	0.08	0.17	47.8
HL30	Yes	Water Consumption	3354	54.6	60.6	0.19	0.28	0.47	60.0
HL31	No	Water Consumption	1502	91.6	101.8	0.14	0.04	0.18	20.0
HL32	Yes	Water Consumption	1641	53.9	59.9	0.09	0.02	0.11	20.0
HL33	Yes	Sli/icer	1908	25.8	44.1	0.06	0.22	0.28	79.1
HL34	Yes	Water Consumption	1963	55.1	61.2	0.11	0.03	0.14	20.0
HL35	No	Water Consumption	3594	54.7	60.8	0.20	0.05	0.25	20.0
HL36	Yes	Water Consumption	1109	62.0	68.9	0.07	0.50	0.57	87.6
HL37	Yes	Sli/icer	3094	37.9	47.3	0.13	0.16	0.29	56.0
HL38	Combined	Sli/icer	2294	46.23	40.94	0.10	0.34	0.45	77.0
HL39	Combined	Sli/icer	3468	46.23	40.94	0.16	0.32	0.47	67.2
HL40	Yes	Sli/icer	2754	36.3	46.8	0.11	0.13	0.24	54.6
HL41	Yes	Sli/icer	2007	61.9	83.3	0.14	0.27	0.41	66.5
TSHL01	Yes	Water Consumption	67	54.0	58.6	0.00	0.01	0.01	60.0
TSHL03	Yes	Water Consumption	877	89.6	99.6	0.08	0.12	0.20	60.0

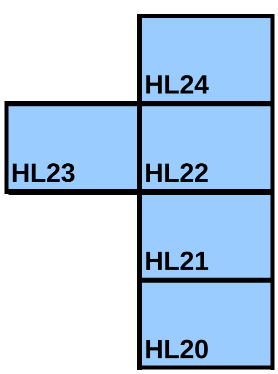
Figure 4-44. Summer 07 HLSS calibration meters (above) and processed DWF parameters for model use (below)

4.4.2 Wet Weather Flow

Gross Versus Net RDII:

The RDII volume can be calculated for each storm and for each flow basin in terms of gross or net contributions in Sli/icer. The gross RDII is total flow subtracted only by DWF and precompensation setting (adjustment due to short-term DWF change – see Section 4.3.6 for details). The net RDII is gross RDII further subtracted by the gross RDII from all immediate upstream basins. Gross and net RDII values are the same for most upstream basins. The Sli/icer manual suggests the use of net RDII because this value pertains to each flow basin separately. However, this approach is not valid for HLSS. The sum of all contributing net RDIIs can exceed the gross RDII, resulting in significant overestimation of the overall RDII volumes.

Figure 4-45 shows an example of potential RDII overestimation based on gross and net values. The basins HL20-HL24 are an isolated portion of HLSS in which the flow eventually reaches the downstream end of GRI. The Sli/icer "Net" columns show the net RDII volumes per inch of rainfall for each flow basin as discrete values, and their accumulated values toward downstream as accumulative values. The accumulative net RDII value at HL20 (1.53 MG/in) is larger than the gross RDII value at HL20 (1.28 MG/in). This implies that the evaluation of RDII volumes solely based on the accumulation of net values for each basin to determine the overall contribution will result in significant RDII overestimation. Therefore, the HLSS team used gross RDII values as guidance to evaluate the system-wide contributions, and then back-calculated the net RDII to estimate capture coefficients for individual flow basins. The back-calculated net RDII values for the HL20-24 flow basins are shown in the "New Net" column.



Flow Basin	Sliicer Net (MG/in)		Sliicer Gross (MG/in)	New Net (MG/in)
	Discrete	Accumulative		
HL24	0.28	0.28	0.28	0.28
HL23	0.33	0.33	0.33	0.33
HL22	0.3	0.91	0.86	0.25
HL21	0.19	1.1	0.94	0.08
HL20	0.43	1.53	1.28	0.34

Figure 4-45. Winter 07 Gross versus net RDII for HL20-24

Calculation of Capture Coefficients from Gross RDII

The next challenge was to accurately estimate capture coefficients from the gross RDII values. As described in Section 4.3.6, the gross RDII is represented as a straight line which consists of a slope (capture coefficient) and X-intersect (depression storage). The net RDII is also represented as a straight line. In order to define a straight line, two points on the line must be fixed. The following two rules were set to develop an empirical relationship:

- Depression storage value from the gross RDII will be used for the net RDII; and
- Net RDII slope is determined so that the new gross RDII matches the Sli/icer calculated gross RDII at two inches of total rainfall.

The following example illustrates the use of these two rules. The meters HL38 and HL39 are for two consecutive basins where HL39 is the only immediate upstream basin to HL38. For summer 2006, the gross RDII relationships for these two basins are:

$Y = 0.95\ (x-0.55)$ for HL38

$Y = 0.46\ x$ for HL39

where, y is the gross RDII (MG/in) and x is the rainfall depth (in).

Figure 4-46 shows the two gross lines for HL38 and HL39, and the processed HL38 net line using the two empirical relationships defined above. The rule 1 estimated depression storage of net HL38 to be the same as that of gross HL38, 0.55 inches. The rule 2 determined the slope of HL38 net RDII using the established depression storage and the Sli/icer gross RDII difference between HL38 and HL39 at two inches of total rainfall. Figure 4-47 shows the comparison between original HL38 gross obtained from Sli/icer (blue) and the processed HL38 gross (green), as the result of summation of HL39 gross and processed HL38 net. As seen in the figure, these two lines meet each other at two inches of rainfall and the difference between the two lines is within 0.1 MG for any rainfall greater than 1.5” but less than 2.5”. A threshold of two inches in rain volume was chosen to determine the net slope because it corresponded approximately to the depth of a 6-month, 24-hr storm (2.14”), and the range of 1.5” – 2.5” covers most of the major global storms.

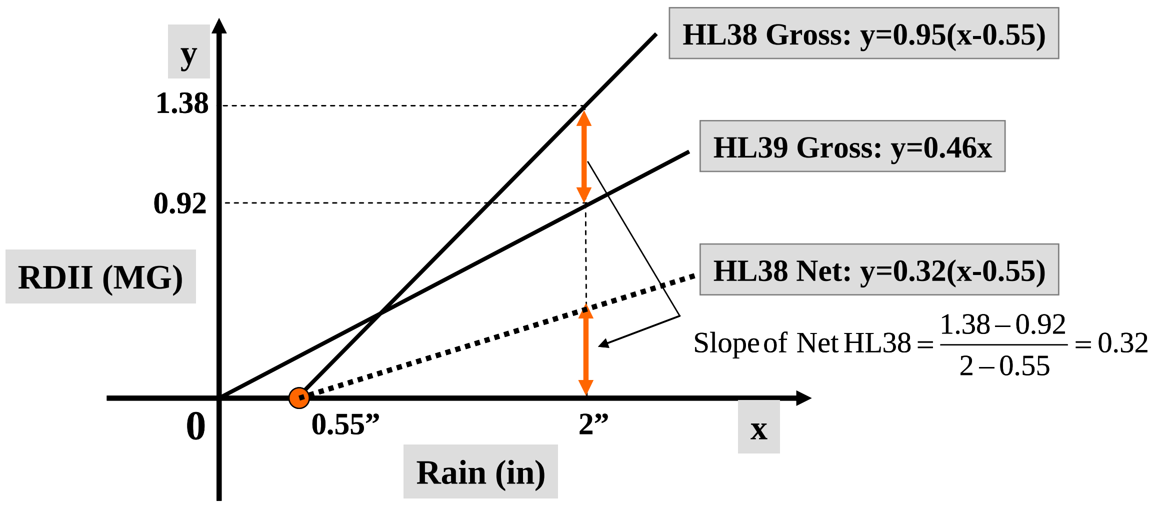


Figure 4-46. Graphical representation of net RDII calculation process

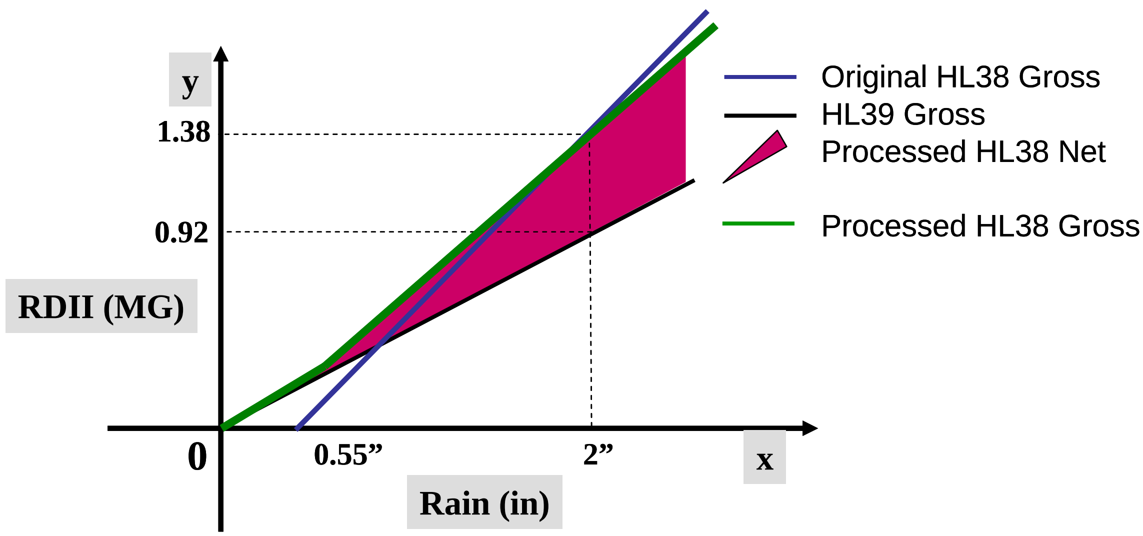


Figure 4-47. Graphical representation of original and processed gross RDII

RDII Imbalance

The flow imbalance issue exists not only in DWF but also in the RDII component. For the given storm events, the RDII imbalance needs to be resolved when the gross RDII from an upstream location is larger than the gross RDII from a downstream location. For the regression analysis, this imbalance needs to be resolved if it occurs at a rainfall depth of approximately two inches. A situation with RDII imbalance is conceptually illustrated in Figure 4-48. In such cases, the second rule for net RDII calculation must be revised as shown below:

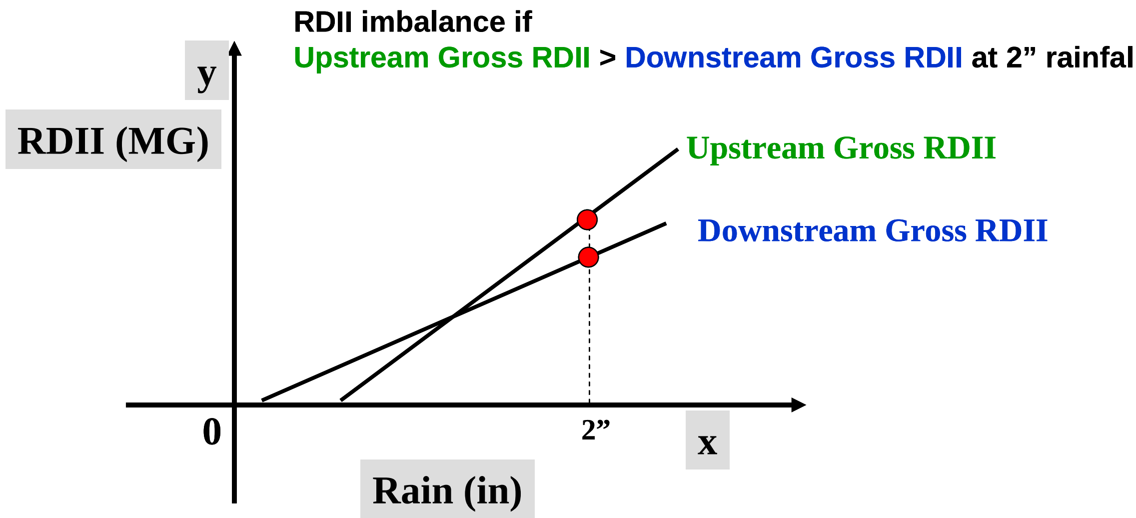


Figure 4-48. RDII imbalance

When an upstream gross RDII is greater than a downstream gross RDII at two inches rainfall depth, the gross RDII for 2" rainfall from a downstream basin should be decomposed into net and upstream gross based on area proportion.

The following example illustrates the modified rule 2. The flow meters HL36 and HL37 are two consecutive basins where HL37 is the only basin upstream of HL36. For summer 2006, the gross RDII relationships for these two basins are:

$Y = 0.31x$ for HL36

$Y = 0.44\,(x-0.59)$ for HL37

where, y is the gross RDII (MG/in) and x is the rainfall depth (in).

Figure 4-49 shows the gross RDII lines for both HL36 and HL37. These lines intersect at a rain depth of approximately two inches. RDII at x=2" should be decomposed into two HL36 and HL37 net RDIIs based on the rule described above (see Figure 4-50). With the decomposed RDII and fixed depression storage, the slope of net RDII lines for HL36 and HL37 can be computed as follows:

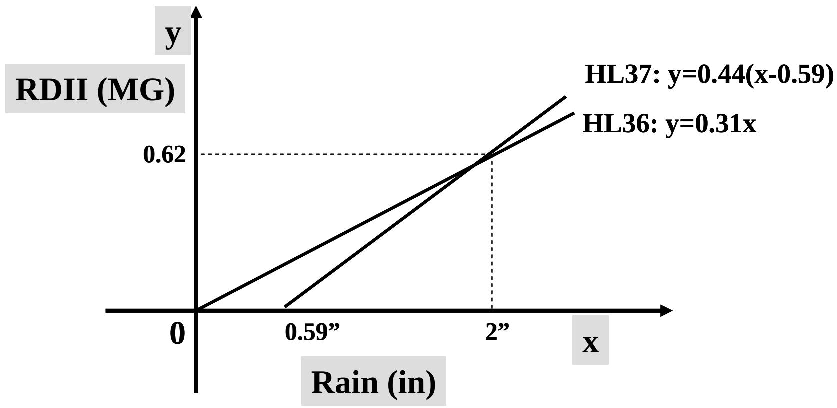
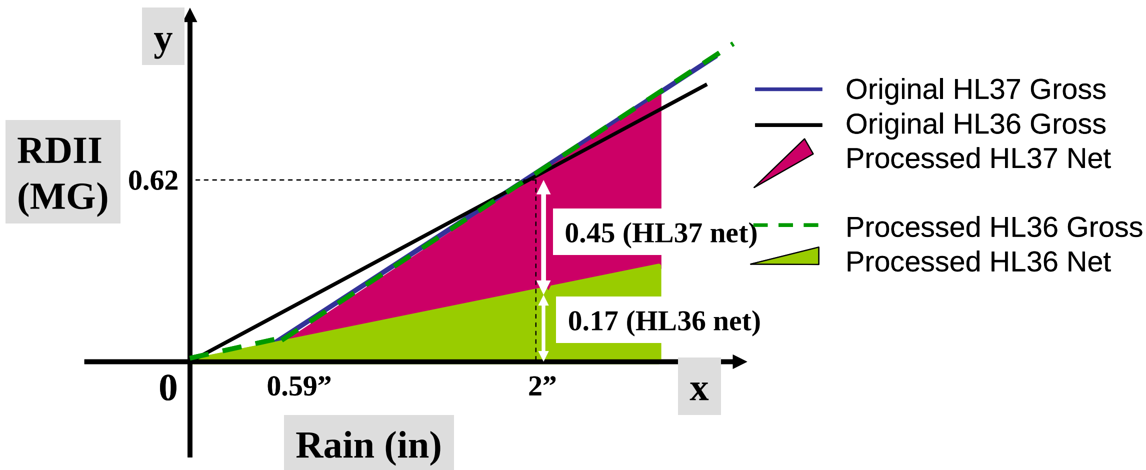


Figure 4-49. Graphical representation of gross RDII for HL36 and HL37



$$\text{Adjusted HL37 Gross I/I for 2" rain}$$
$$= \text{HL36 Gross I/I for 2" rain} \cdot \frac{\text{HL37 Area}}{\text{HL37 area} + \text{HL36 Area}} = 0.62 \cdot \frac{179}{179+65} = 0.45\,(\text{MG})$$

Figure 4-50. Graphical representation of original and processed RDIIs for HL36 and HL37

$$\text{Adjusted HL36 Capture Coefficient} = \frac{0.62-0.45}{2} = 0.085\,(\text{MG/in})$$

Y = 0.085x

$$\text{Adjusted HL37 Capture Coefficient} = \frac{0.45}{2-0.59} = 0.32\,(\text{MG/in})$$

Y = 0.32 (x-0.59)

Processed Capture Coefficients in HLSS

The Sli/icer gross RDII separation methodology cannot be applied for systems that have irregular discharges (e.g., pump discharge). In HLSS, there is a significant irregular pump discharge from the Washwater Lake, which makes the estimation of capture coefficient quite complicated along the GRI and HLI for HL28 and the downstream metering locations. Therefore, the capture coefficients for these interceptor basins were initially set to an average HLSS capture coefficient, and were further adjusted during model calibration.

Except for these interceptor basins, the capture coefficient in non-dimensional form was calculated for each flow basin for the summer and winter seasons. Figure 4-51 shows the processed capture coefficients excluding all the interceptor basins downstream of HL28. The figure was color coded from white to blue based on the severity of inflow/infiltration as indicated by the capture coefficient values. Two conclusions can be derived here:

- RDII is more severe for flow basins contributing to the upstream portion of GRI
- RDII is more severe in winter than in summer for whole HLSS.

The processed seasonal capture coefficients and depression storages were applied to the hydraulic model as non-calibration parameters for each flow basin except for the interceptor basins where capture coefficients could not be determined by the flow balance analysis. The model representation of RDII in InfoWorks with seasonal capture coefficients is explained in section 5.

In summary, this section described the data sources used for model development, the incorporation of rainfall monitoring data into the model, and the use of hydraulic modeling data analysis in flow component development. In addition, section 4 outlined the procedure for resolving flow imbalances for both dry and wet weather flow. The flow balance analysis plays an important role in connecting the Sli/icer data analysis to the hydraulic model.

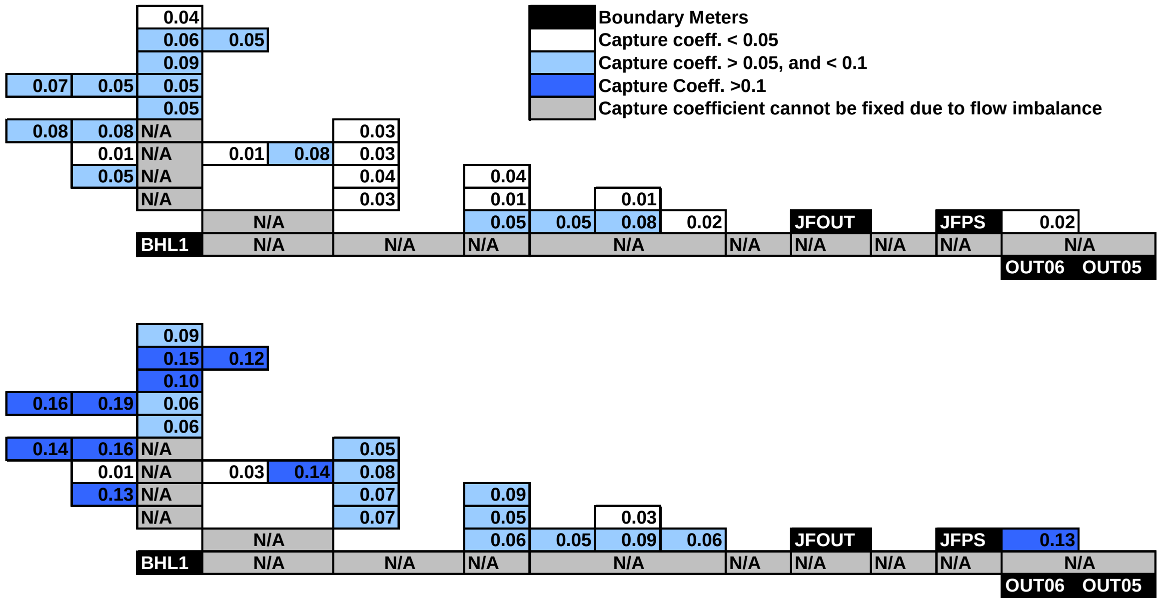


Figure 4-51. Processed summer (above) and winter (below) capture coefficients in HLSS

THIS PAGE INTENTIONALLY LEFT BLANK

SECTION 5 – MODEL DEVELOPMENT

This section describes the overall approach used for HLSS model development. Several guidelines provided in the CD and BaSES manual were used in this process. The overall goal was to construct an optimal model configuration for HLSS that would support localized hydraulic analyses as well as a regional analysis by the City.

5.1 MODEL NETWORK CONSTRUCTION

5.1.1 Macro Model to Micro Model

The macro model developed by 1015 was used as the initial setup. It was carefully reviewed to identify sewer sections that were not included in the macro model but were needed in the micro model due to CD or BaSES requirements. This included pipes 10 inches and larger, historical and engineered SSO locations, and any 8-inch sewers necessary for local capacity evaluations. Figure 5-1 shows example locations where 8" pipes were added to be able to simulate: (a) known engineered SSOs that were active during the flow monitoring period (e.g., SSO 126 and SSO 128) and (b) locations with historical surcharging or flooding events. These pipes, manholes and other pertinent sewer elements (e.g., sluice gates) were added to complete the comprehensive micro model layout. Figure 5-2 shows a comparison of the macro and micro model extents, with the original macro network shown in red. The final HLSS micro model network includes approximately 1,000 nodes and links (excluding the Jones Falls force main section which has approximately 150 manholes).

5.1.2 Representation of Engineered SSOs

The 12 engineered SSO locations active in HLSS during the flow monitoring period were explicitly included in the hydraulic model. For each location, the invert elevation and overflow pipe size were obtained from the Paragraph 8 flow monitoring site sheets. Figure 5-3 shows the distribution of these locations and an example model setup for SSO 132. In this example setup, the overflow pipe is 18" in diameter with an invert 8.9 feet higher than the manhole invert elevation. In the model simulation, wastewater released through the overflow pipe represents a potential overflow. The model tracks the overflow volume and duration at each manhole and overflow pipe location in order to establish the overall water balance and also to extract these values for guiding the alternatives analysis for eliminating the SSOs.

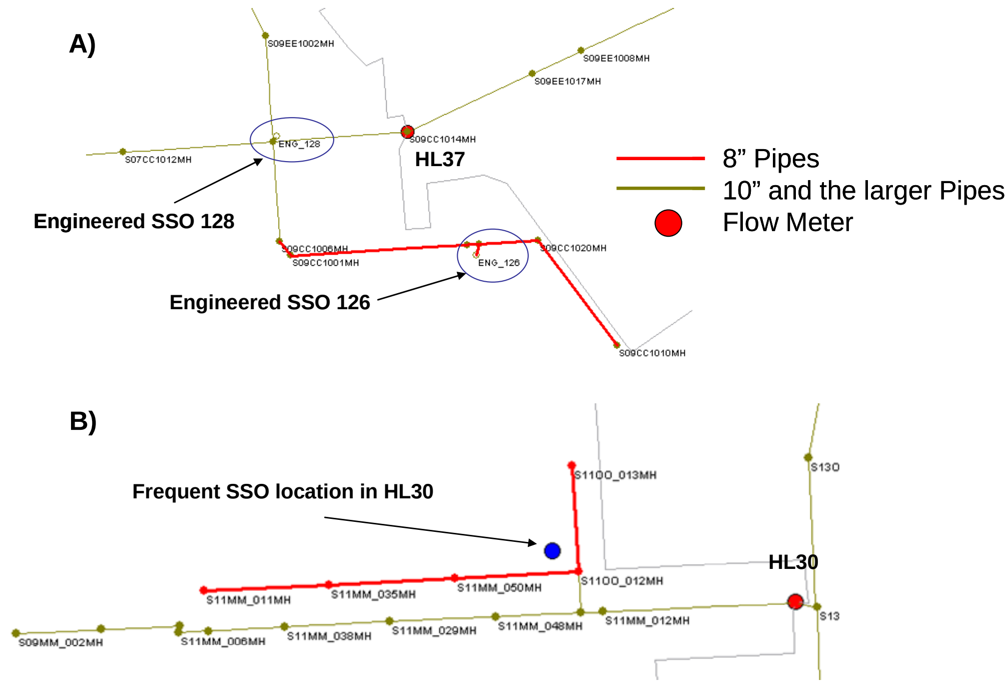


Figure 5-1. Example Locations where 8" Pipes were Added to the Model Extent

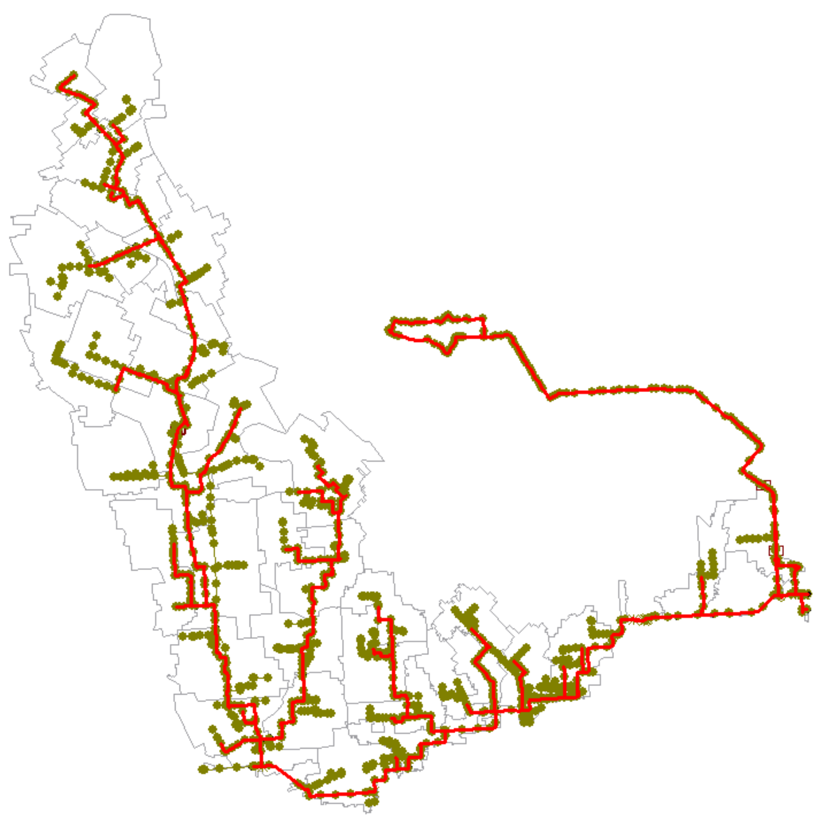


Figure 5-2. Macro-model Extent (shown in Red) on the HLSS Micro-model Network

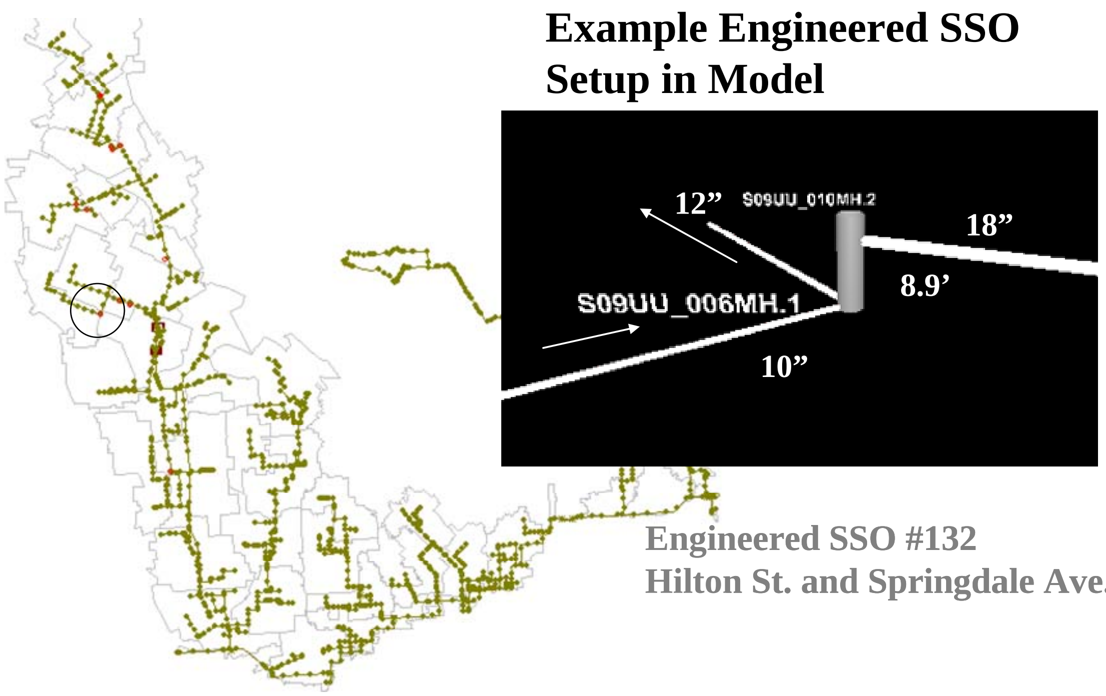


Figure 5-3. Engineered SSOs in Model Extent and an Example Model Setup for SSO 132

5.1.3 Model Updates Based on Field Data

As described in Section 4, three types of field inspections were performed to collect the necessary data: land surveys, manhole inspections, and CCTV/sonar inspections. The manhole X and Y coordinates obtained from land surveys; rim elevations, pipe inverts, and pipe diameters confirmed during manhole inspections; as well as the sediment depths observed during sonar inspections were imported into the micro model, subsequent to validation by the ADS/JMT staff. The HLSS portion of the City’s GIS database was updated concurrently, so that the database and model had consistent information and could be linked to facilitate future asset management efforts by the City. To date, 650 modeled pipes have invert elevations from field data (i.e., from both land survey and manhole inspections) and 950 modeled manholes have rim elevations from land survey data out of a total of 1,000 model nodes.

During model construction, the InfoWorks CS model’s data source flagging function was used to differentiate between the various sources of data. The flags used in the HLSS micro model are listed in Table 5-1. Most flags were inherited from the macro model, except for three new flags which were added by the HLSS team.

For example, there were several occasions where the slope of a pipe became negative when pipe inverts from the field data were imported into the model. In such cases, one of the pipe’s inverts was changed so that the pipe has a reasonable downward slope. FX flags were applied to the modified pipe inverts in InfoWorks so that the erroneous field data was removed from the model.

Table 5-1. User Defined Flags in InfoWorks Referring to the Data Sources.

Macro Model Flags

Flag	Data Flag Description
#A	Asset Data
#D	System Default
#G	Data from GeoPlan
#I	Model Import
#V	CSV Import
AD	Assigned values by modeler
AS	inferred or assumed
DV	Default IWCS value - applied during initial import of geo-database
GD	Dump of City's geodatabase dated 11-13-2006
GI	Data imported from GIS
RI	Record Information
SR	Value obtained from Site Report
WA	Wastewater Analyzer's Office Model

Newly added Flags

Flag	Data Flag Description
AB	As-Built Drawings
FD	Data from Field
FX	For places where field data are questionable

5.1.4 Pre and Post SC812 Relief Sewer Representation

When sewer system alterations (e.g., closure of certain engineered SSOs or cleaning of sewers) occur during the study period, it is necessary to create multiple networks which reflect the changes for specific dry and wet weather events used for model calibration. The SC812 relief sewer was constructed by the City to connect the sewers located downstream of HL31 to the sewers downstream of HL25. This relief sewer was added in February 2007 to alleviate SSOs that frequently occurred near the Washwater Lake and to increase the capacity of GRI. Figure 5-4 shows the sewer network near the Washwater Lake before and after the SC812 relief sewer was installed. This sewer diverts all flows from the main interceptor to the relief pipe unless it is surcharged to the extent that the water level rises to the existing 24” sewer at the diversion chamber. Figure 5-5 shows the detailed setup of this diversion chamber.

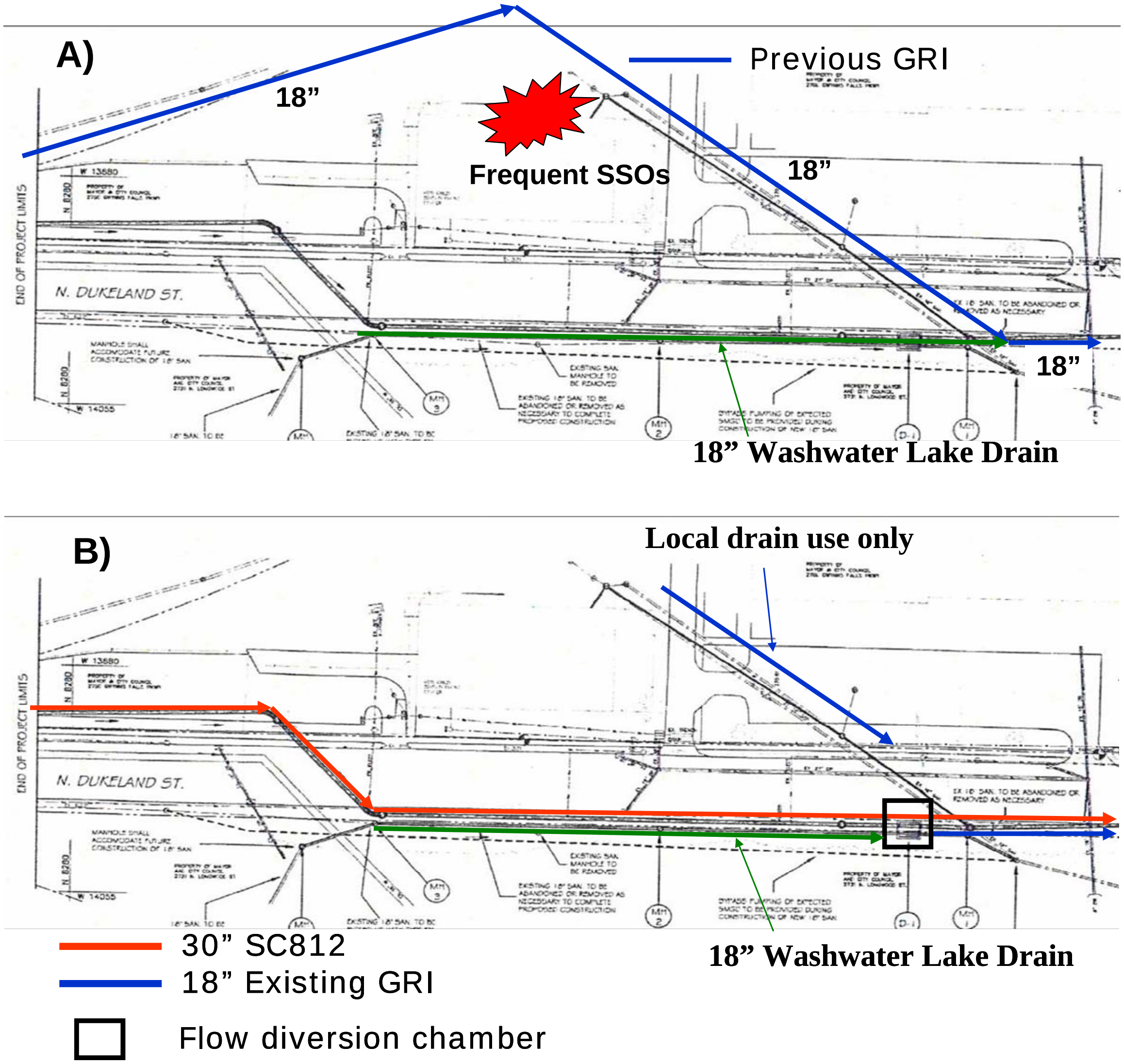


Figure 5-4. Sewer Network near Washwater Lake A) before and B) After SC812 was Installed

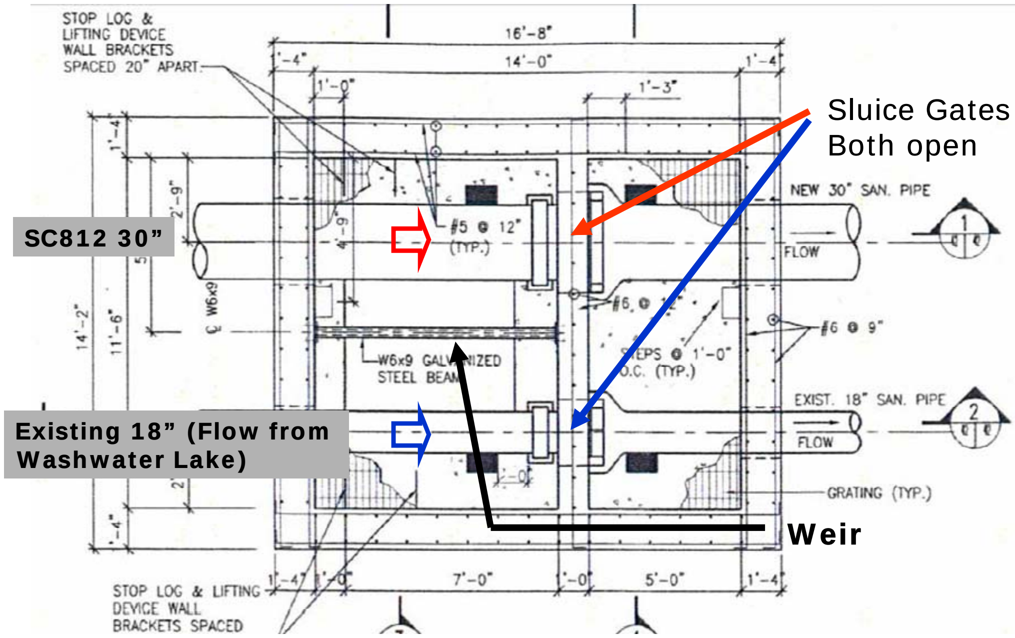
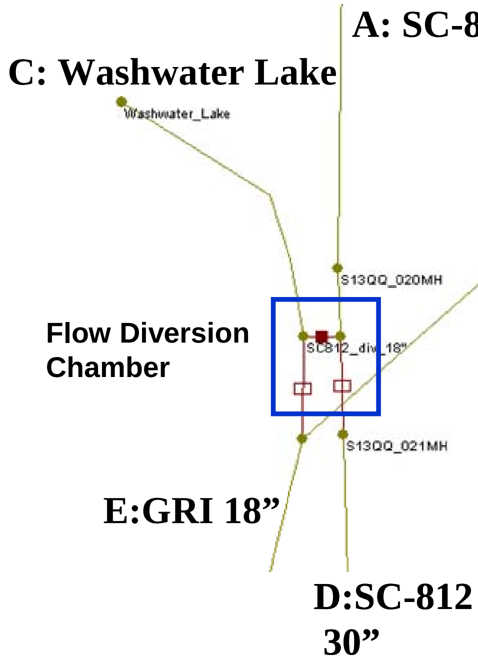


Figure 5-5. SC-812 diversion chamber drawing

In order to minimize any data discrepancies, the pre- and post-SC812 InfoWorks networks are identical except for the different valve open and close setups. Figure 5-6 shows the model representation of pre- and post-SC812 systems and the diversion chamber. For pre-SC812, water comes from the 18” GRI (Location B) and the Washwater Lake (Location C) and flows out to the 18” GRI. For post-SC812, water comes from the 30” SC812 (Location A) and the Washwater Lake and flows out to both SC812 (Location D) and the 18” GRI (Location E). Flow control valves were placed in the model to divert GRI flow to the 18”diameter old GRI pipe for pre-SC812 and to a new 30” SC812 relief pipe for post-SC812.

5.1.5 Model Network Validation

The model networks were subjected to a thorough validation process, in which the InfoWorks model output lists of warnings and errors according to common network connection rules and customized engineering guidelines. The errors were fixed by the HLSS team to ensure correct representation of the sewer system prior to running model simulations.



	Incoming	Outgoing
Before Feb 14th 07 (Pre-SC812)	B and C	E
After Feb 14th 07 (Post-SC812)	A and C	D and E

Figure 5-6. Model Setup for the SC812 Representation

5.2 SUBCATCHMENT DELINEATIONS

The HLSS flow basin areas were further divided into subcatchments to more accurately represent flow entry into the sewer system under both dry and wet weather conditions. The DWF and wet weather model parameters for each subcatchment were input into the model at the end node of each subcatchment.

For DWF, the 2000 census population within each subcatchment and water consumption rates were used to estimate the flows generated for the subcatchment. For wet weather, RDII simulated by InfoWork CS’s RUNOFF module was also calculated for each subcatchment. For sanitary sewer systems, the subcatchment parameters such as surface roughness, slope, and overland flow width do not have real physical significance in comparison to the modeling of combined or storm drainage areas that are designed to convey all runoff towards the sewers. However, these parameters were used to model RDII as a function of the rainfall depth and intensity. The parameters also accurately allocate the inflow points of RDII to be more consistent with the hydraulic connectivity of the sewer network.

The subcatchments in the HLSS model were delineated following the guidelines provided in the BaSES manual:

- Subcatchment boundaries were generally drawn at hydraulic control points such as flow diversion chambers, pump stations, constructed overflow points, significant tributary junctions, and flow monitor locations;

- Large parcels of land such as parks, golf courses and freeways not connected to the collection system were excluded;
- Subcatchment delineations always ended at a manhole;
- Model load points were assigned to best represent the effects of flows entering system; and
- “Dry pipes” were avoided so as to eliminate model elements that did not receive flow from an upstream load point.

Figure 5-7 shows an example of delineated subcatchments in the HLSS model. In total, there are 321 subcatchments ranging in size from approximately 1 acre to 100 acres, with an average area of 14 acres.

For each subcatchment, population, ground slope, and dimensions were pre-assigned using GIS. Population was assigned using a GIS intersection process with the census 2000 layer and model subcatchment layer. For ground slope, the average slope for each model subcatchment was calculated in GIS and assigned for each subcatchment. A “dimension” in InfoWorks refers to the runoff surface width. First, a default runoff surface length was defined as the distance between subcatchment centroid to the basin outlet node, calculated in GIS. Then, the initial value for dimension, or runoff surface width, was assigned as the subcatchment area divided by the defined runoff surface length. Ground slope and dimensions were subject to minor changes during model calibration.

5.3 FLOW COMPONENTS

Total flow in a sanitary sewer system consists of base ground water infiltration (BI), sanitary flow from residential and commercial areas, waste flow from significant industrial dischargers, and the RDII. The flow components segregated using Sli/icer during data review had to be translated to an InfoWorks compatible format. The BI and DWF are the primary components that were imported into the model.

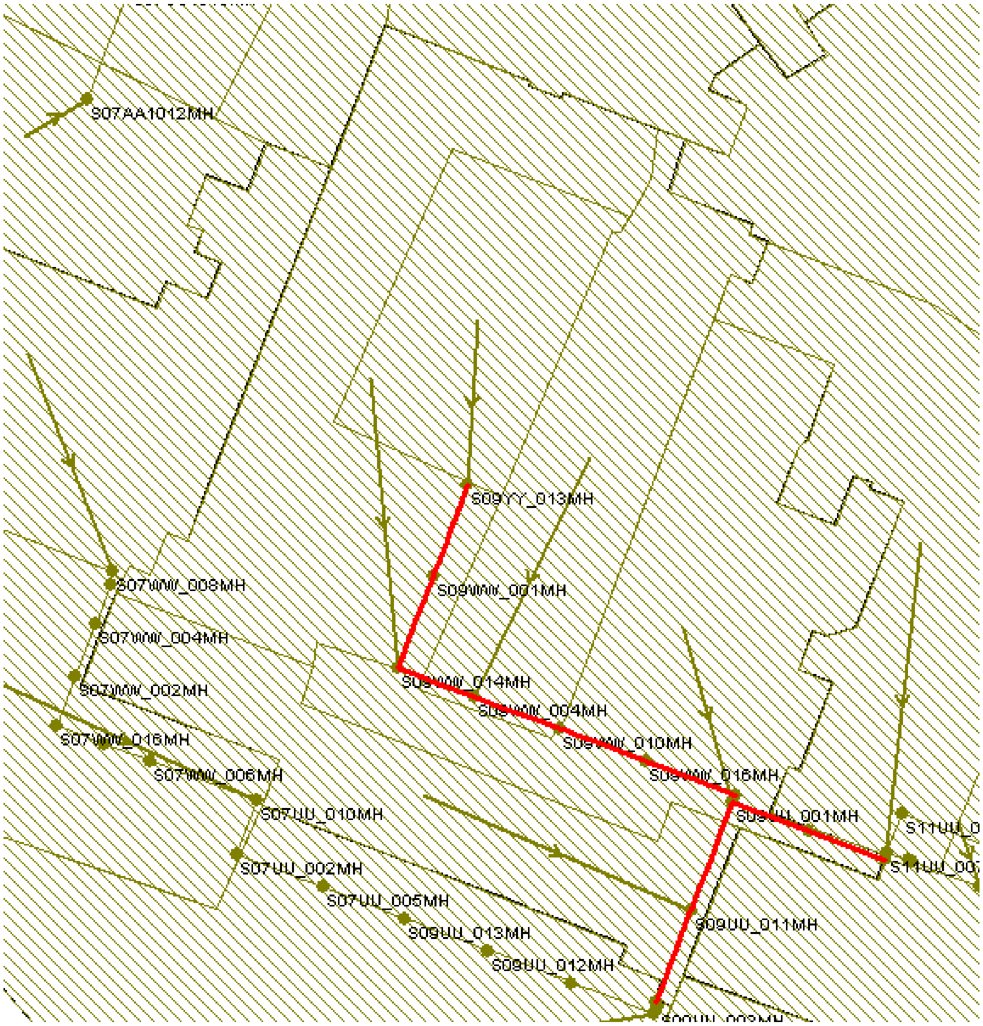


Figure 5-7. Example of Subcatchment Delineation in InfoWorks

In InfoWorks CS, there are a number of ways in which DWF components can be provided as input, depending on how the flow components are characterized (see Table 5-2).

Table 5-2. Inflow Assignment Types in InfoWorks

INFLOW TYPE	ASSIGNED TO	CHARACTERISTICS
BASE LOW	Subcatchment	Provided as constant flow input
ADDITONAL FOUL FLOW	Subcatchment	Provided as constant flow input
TRADE FLOW	Subcatchment	Can be used for flows with quantifiable hourly, daily, or seasonal variations
WASTEWATER FLOW	Subcatchment	Defined with population, waste water per capita usage, and variation pattern
INFLOW	Node	Defined as time-series

Based on the BaSES guidance, wet weather RDII flow components are calculated at the subcatchment level using the InfoWorks RUNOFF module, given the rainfall and associated parameters.

5.3.1 Groundwater Base Infiltration

The BI for each flow basin was initially processed using Sli/icer and was adjusted when the net flow rate or DWF decomposition into WWP and BI were questionable. Since BI can vary seasonally, separate BI rates were processed for the three seasons: Summer 2006, Winter 2007 and Summer 2007. These values were entered as trade flow in InfoWorks for the three seasons, and distributed between each subcatchment within the flow basin based on the area proportions. For several sites that had inaccurate data, assumptions were made to estimate the BI values.

5.3.2 Wastewater Per Capita Usage and Time Variations

Sli/icer provided WWP rate (Net WWP) for each flow basin by calculating the average DWF during dry days with no preceding rainfall for a period of 48 hours and then subtracting the estimated BI. Since the dominant land use in HLSS is residential, a combination of population and WWP rate was used to represent wastewater generation rates from the residential areas.

A wastewater profile was generated for each flow basin to represent the per capita water usage rate. To calculate the per capita rate, population data from the 2000 census was obtained and the census blocks were overlaid with the flow basin and subcatchment boundaries. The per capita water usage was calculated as the ratio of WWP rate to the total population of a flow basin. This water usage was then uniformly applied to all subcatchments within the basin, along with the population of the individual subcatchment, to generate population-based WWP rates.

The calculated per capita rates were also verified using water usage records obtained from the City. Typical literature values for residential areas vary between 30 to 150 gallons per day (GPD). According to the BaSES manual, wastewater flow rates ranges from 30 to 60 gallons per unit for older homes and from 75- to 150 gallons per unit for newer homes. When the per capita rates are out of the typical range, it may indicate: (a) the presence of mixed land use, including large industrial, institutional or commercial influences whose wastewater flows are different from a typical residential land use or (b) inaccuracies in flow monitoring data or insufficient data used to compute the net WWPs. In these cases, the City's water consumption records were used to supplement the estimation of WWP values.

The WWP rate, population and wastewater usage rate for each flow basin were entered in an InfoWorks compatible format. These values were specific to each time period chosen for the hydraulic model calibration: Summer 2006, Winter 2007, and Summer 2007 - the three seasons defined in Sli/icer global settings by 1015.

In addition to the per capita rate, hourly DWF diurnal peaking factors were provided as input in the wastewater profile to model the variations during a typical day. Different patterns for weekdays and weekends were generated using Sli/icer, processed and then imported to InfoWorks.

5.3.3 Ashburton WFP Wastewater Discharge

Both filter backwash flow and sedimentation basin discharge from the Ashburton WFP enters the HLSS system. In the HLSS model, discharges developed during the flow analysis were provided as time series inflows to model nodes representing the exact discharge locations. The discharge from the sedimentation basin occurs every hour and peaks at about 1 MGD, flowing directly to the GRI near Liberty Heights Avenue. The filter backwash water discharges through a gabion structure in the Washwater Lake and is pumped into the SC812 diversion chamber with a flow rate of up to 10 MGD. Figure 5-8 shows the location of inflow nodes for Ashburton WFP discharges in the pre-SC812 and post-SC812 model networks.

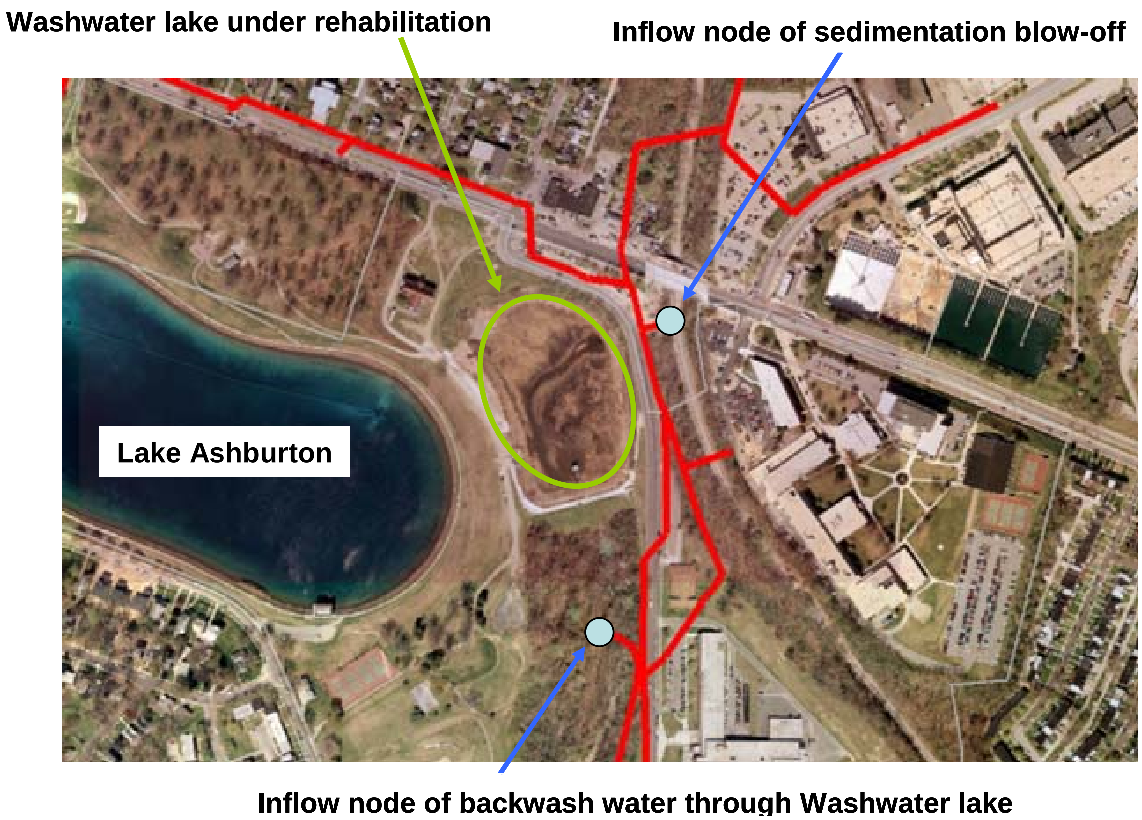


Figure 5-8. Inflow points for Ashburton WFP Discharges

5.3.4 RDII

In order to characterize RDII in the HLSS system, Radar rainfall data for global storm events was used to determine wet weather flows. The Radar data includes hyetographs for the entire city-wide grid, a part of which covers the HLSS drainage area. Using an automated GIS procedure, the closest Radar grid was identified for each InfoWorks model subcatchment within the HLSS, and the Radar rain data from this grid was used to characterize the inflow for that sub-basin.

The wet weather flow component, RDII, was analyzed using Sli/icer for each monitored flow basin. The relationship between RDII and rainfall received in a drainage basin is expressed as:

$$V = C\ A\ (D - DS)$$

where V is RDII volume, D is rainfall depth, A is catchment basin area, and DS is the initial rainfall loss or depression storage. For wet weather events, the coefficient C is influenced by several factors including the age and condition of the system, prevalence of direct (illicit) connections, antecedent soil moisture conditions, and ground water levels.

The Sli/icer estimated winter and summer I/I capture coefficients and depression storage values for each flow basin were provided in the model as initial values. All subcatchments within a flow basin were assigned the same C and DS values. Table 5-3 summarizes the winter and summer capture coefficients and DS values for the flow basins as derived from Sli/icer.

RDII Model Setups in Summer and Winter:

Since the RDII in winter was observed to be higher than in summer, the HLSS team explored technical approaches to induce an additional RDII during winter. For summer wet weather events, runoff was generated from a single RDII surface with fixed DS, fixed capture coefficient, and variable routing values. For winter, however, the runoff was generated from two different RDII surfaces with the same winter depression storage - one with a summer capture coefficient and another with a capture coefficient to represent the additional winter RDII as shown in Figure 5-9. To create the winter season network, the additional RDII surfaces and parameters were added to the existing summer season configuration. In the same manner, a year-round model can be easily created using the winter network but with the additional RDII cut by half. This allows a baseline analysis to be done either with summer, winter, or the year-round network.

Table 5-3. Depression Storage and Capture Coefficient Values for Summer and Winter Study Periods in InfoWorks.

	Summer		Winter	
Meter	Capture coefficient (%)	Depression storage (in)	Capture coefficient (%)	Depression storage (in)
HL41	4.1	0.00	9.1	0.00
HL40	5.0	0.00	12.1	0.00
HL39	5.7	0.00	15.0	0.00
HL38	8.8	0.55	9.8	0.00
HL37	6.7	0.59	15.6	0.07
HL36	4.7	0.00	19.1	0.00
HL35	4.7	0.20	5.7	0.00
HL34	4.9	0.31	5.7	0.00
HL33	7.8	0.39	13.6	0.20
HL32	8.2	0.30	16.4	0.30
HL31	1.0	0.20	2.0	0.00
HL30	0.5	0.00	1.3	0.00
HL29	1.5	0.38	3.3	0.39
HL28	1.0	0.20	2.0	0.00
HL27	4.8	0.16	12.5	0.10
HL26	1.0	0.20	2.0	0.00
HL25	1.0	0.20	2.0	0.00
HL24	3.3	0.45	5.1	0.00
HL23	8.0	0.25	14.5	0.00
HL22	2.6	0.00	8.4	0.00
HL21	4.1	0.44	7.2	0.00
HL20	3.3	0.06	7.2	0.00
TSHL03	1.0	0.20	2.0	0.00
HL19	1.0	0.20	2.0	0.00
HL18	1.0	0.20	2.0	0.00
HL17	3.7	0.00	8.6	0.00
HL16	1.3	0.27	4.7	0.00
HL15	4.6	0.37	5.7	0.37
HL14	1.0	0.20	2.0	0.00
HL13	5.4	0.40	5.4	0.00
HL12	0.9	0.00	3.3	0.00
HL11	7.5	0.23	9.3	0.00
HL10	2.2	0.20	5.6	0.00
HL09A	1.0	0.20	2.0	0.00
HL09	1.0	0.20	2.0	0.00
HL08A	1.0	0.20	2.0	0.00
HL08	1.0	0.20	2.0	0.00
HL07	1.0	0.20	2.0	0.00
HL06	2.0	0.00	12.5	0.38

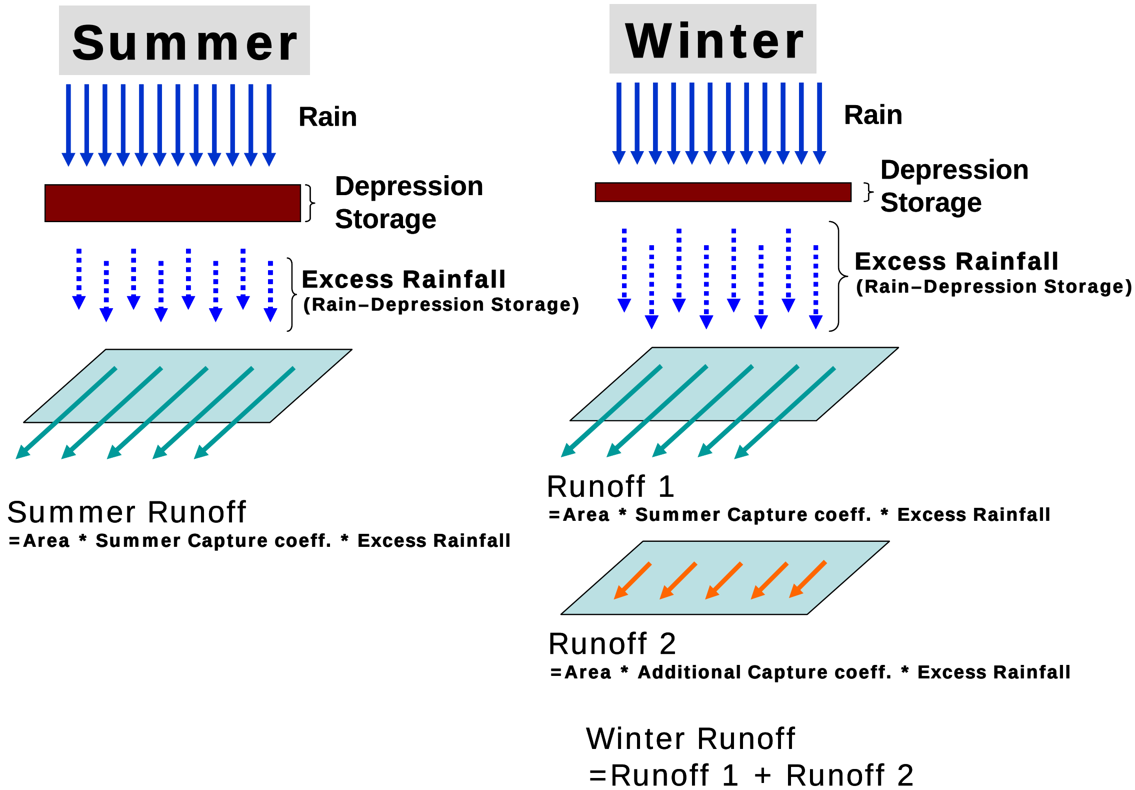
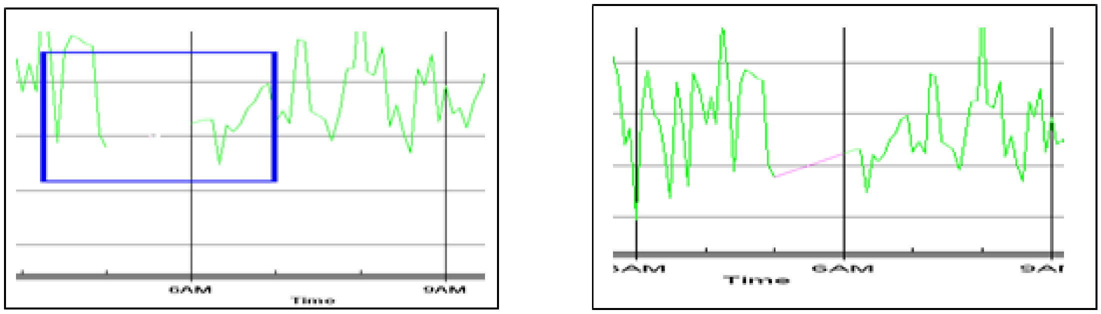


Figure 5-9. Conceptual diagram of summer and winter RDII generator in the model

5.4 MODEL BOUNDARY CONDITIONS

As described in Section 2, flows from the Baltimore Street Diversion, Lower Jones Falls Interceptor, Jones Falls Pump Station force main, and the Eastern Avenue Pump Station force main flow into the HLSS system. These influence the HLI's ability to convey flow to the Outfall Sewershed during dry and wet weather periods. In order to simulate these external influences appropriately during model calibration, measured data at the boundary meters was processed to generate time series boundary inflows. A linear interpolation technique was used to fill data points missing for less than 2 hours for all boundary meters. For data points missing for more than 2 hours, average flow of the site was used as the surrogate value (see Figure 5-10).



Data missing for about 2 hrs at BHL1 on 8/11/06.

Data gap filled using linear interpolation method for the missing period.

Figure 5-10. Linear Interpolation to fill in Missing Data

For model projection analyses involving future sewer rehabilitation alternatives, the boundary flow or water level time series conditions will be provided by 1015. The HLSS team will incorporate this time series data, along with the DWF and RDII generation within HLSS, to assess the overall hydraulic conditions of the drainage area.

THIS PAGE INTENTIONALLY LEFT BLANK

SECTION 6 – MODEL CALIBRATION AND VALIDATION

6.1 MODEL CALIBRATION AND VALIDATION

The accuracy and performance of a computer model is best measured by its ability to reproduce the actual system performance that it is designed to simulate. Model calibration and validation is a process of adjusting appropriate model parameters to achieve the desired accuracy of model reproduction of the observed historical events.

A calibration and validation process first involves a selection of several simulation periods (events) for which data is readily available or has been collected. It is important to select periods that are also representative of the conditions that will be simulated by the model such as either typical or extreme rainfall events, or both, in addition to normal and/or seasonal dry weather conditions. Several periods can be selected during a calibration process such that model parameters are chosen and adjusted to reasonably reproduce actual data within acceptable and justifiable model parameter ranges. The calibration process can result in several sets of model parameters that may reasonably simulate individual events, but may need to be combined to simulate different future conditions that the model will be used to analyze. Therefore, validation periods are simulated once a set of model calibration parameters has been selected. The accuracy and performance of the model can then be assessed by its ability to independently simulate validation events without adjusting any model parameters. If the model performance for validation periods is not within acceptable tolerance levels, model calibration will need to be repeated with the selection of a different set of parameters, with further validation to enhance its robustness.

Following guidelines in the BaSES manual, the HLSS model calibration and validation was performed in two steps, with the first one for dry weather conditions and the other for wet weather conditions. The purpose of DWF calibration/validation is to develop accurate flows attributed to BI and base wastewater flow from residential areas and industrial/commercial dischargers into the sewer system. The RDII modeling is then achieved through calibration/validation during rain events.

The data collected at flow meters installed during the city-wide monitoring program were used to evaluate the modeling results. The following methods suggested in BaSES were adopted for evaluating the model calibration/validation results and determining the adequacy of calibration for application to future baseline and alternatives analyses:

- Time series comparisons of observed and modeled dry and wet flows, velocities and water depths

- Statistical goodness-of-fit plots of observed and modeled wet event peak flows and volumes

The details of HLSS model calibration and validation are provided in the following sections.

6.2 DRY WEATHER CALIBRATION

The dry weather calibration verifies that the model representation of various DWF components is appropriate and adequate. These components include BI and WWP from the various flow basins, inflows from boundary locations (e.g., Lower Jones Falls interceptor and Eastern Avenue Pumping Station force main) and discharges from the Ashburton WFP (i.e., sedimentation basin discharge and filter backwash water from the Washwater Lake). This process establishes flow conditions in sewers before the complex RDII flow conditions are introduced during wet weather periods.

6.2.1 Event Selection

Several DWF events were selected from the flow basin monitoring period to support the dry weather calibration process. The primary rationale for event selection was to choose dry periods with no rainfall for at least 48 hours prior to the event so that there would be little to no residual moisture that might affect infiltration during these periods. In accordance with BaSES guidance, the dry weather periods were chosen to extend for periods ranging from 5 to 12 days in order to characterize the possible variations between the weekday and weekend water usage patterns. Dry periods from all the three seasons defined in Sli/icer were chosen to adequately characterize the seasonality in DWF patterns.

The selection of events was also dependent on system configuration changes. For example, the relief pipe SC812 was constructed and operated when the system-wide flow monitoring was in progress in the HLSS. Therefore, dry periods were chosen to represent both the pre and post-SC812 construction that might exhibit differences in system behavior.

Table 6-1 exhibits the events chosen by the HLSS team for dry weather flow calibration.

Table 6-1. Proposed Dry Weather Flow Calibration Events

Event Number	Event Period	Season	Duration (days)	SC-812 in service
1	May 27 - 31, 2006	Summer 2006	5	No
2	August 11 -22, 2006	Summer 2006	12	No
3	December 4 - 12, 2006	Winter 2006	9	No
4	February 5 - 13, 2007	Winter 2006	9	No
5	March 28 - April 3, 2007	Summer 2007	7	Yes
6	April 30 - May 10, 2007	Summer 2007	11	Yes

6.2.2 Dry Weather Calibration Parameters

Flow Rate:

The goal for DWF calibration was to properly characterize the DWF components. In order to demonstrate this, the modeled DWF hydrographs were compared with monitored data at the good DWF meters for each of the events. The calibration parameters used for flow rate adjustment was the amount of base infiltration for bad meters.

Significant dischargers other than the Ashburton WFP were not included separately as point discharges in the model. These discharges were lumped with the WWP for each flow basin.

Flow Depth and Velocity:

The process of calibration should well establish the water balance as well as represent the local hydraulic conditions adequately. In addition to the flow hydrographs that establish water balance, observed water depth and velocity data were compared with modeled data as part of the calibration process. Pipe slope, size, cross-sectional shape, pipe roughness, and sewer network connectivity were some of the important factors reviewed during the dry weather calibration process. In addition, the parameters such as sedimentation depth in pipes were reviewed and adjusted as necessary.

In the HLSS dry weather calibration, the following key factors were critically reviewed to achieve a good correlation between monitored and modeled flow depths and velocities at the flow metering locations: pipe size, sediment depth, roughness, and slopes of immediate upstream and downstream pipes (in cases where there was uncertainty in slopes due to data derived from two different sources). Among those, the pipe size, sediment depth, and pipe slopes were not adjusted for almost all the cases from various data sources (i.e., land survey, manhole inspection, flow meter site sheets, and as-built drawings). Therefore, pipe roughness was used as the primary calibration parameter for flow depth and velocity adjustments.

6.2.3 Dry Weather Flow Calibration Evaluation

The adequacy of DWF calibration was checked using two different approaches. Our first approach was to compare the time-series plots of simulated and observed DWF for each event on a meter by meter basis and generate a DWF adequacy check table as seen in Appendix 1 which shows the numerical difference between the observed and predicted peak flow, volume and depth. The other approach was to compare the average flow rate between simulated and observed data on a system-wide basis, so that the flow progression from upstream to the downstream end of HLSS could be used to check the calibration adequacy. These two approaches are discussed below.

Meter-specific Time-series Comparison:

Appendix 1 shows the DWF time-series plots for all the flow meter locations in HLSS and for all the 8 dry weather flow events. The HLSS was divided into five groups shown below for discussion purposes. Specific observations and explanations related to dry weather calibration are provided subsequently for each group for meters utilized for DWF calibration defined in Figure 4-40, 4-41, and 4-42 depending on the season:

a. Upper Gwynns Run Interceptor basins (HL34 – HL41)
b. Lower Gwynns Run Interceptor basins (HL25 – HL33)
c. Second Gwynns Run Interceptor and TSHL03 (HL20-HL24, TSHL03)
d. Minor flow basins contributing to HLI (HL15 – HL17, HL10 – HL13, HL06), and
e. Flow basins along HLI (HL19, HL18, HL14, HL09A, HL09, HL08A, HL08, HL07, and TSHL01)

Group A: Upstream Gwynns Run Interceptor Basins (HL34 – HL41)

From the middle of the HL41 basin to the HL31 flow meter, some portions of HL37, 36, 33, and HL32 flow basins along GRI were relined by SC807 project. Therefore, the as-built drawings with profiles were available for these sections to verify pipe sizes and slopes.

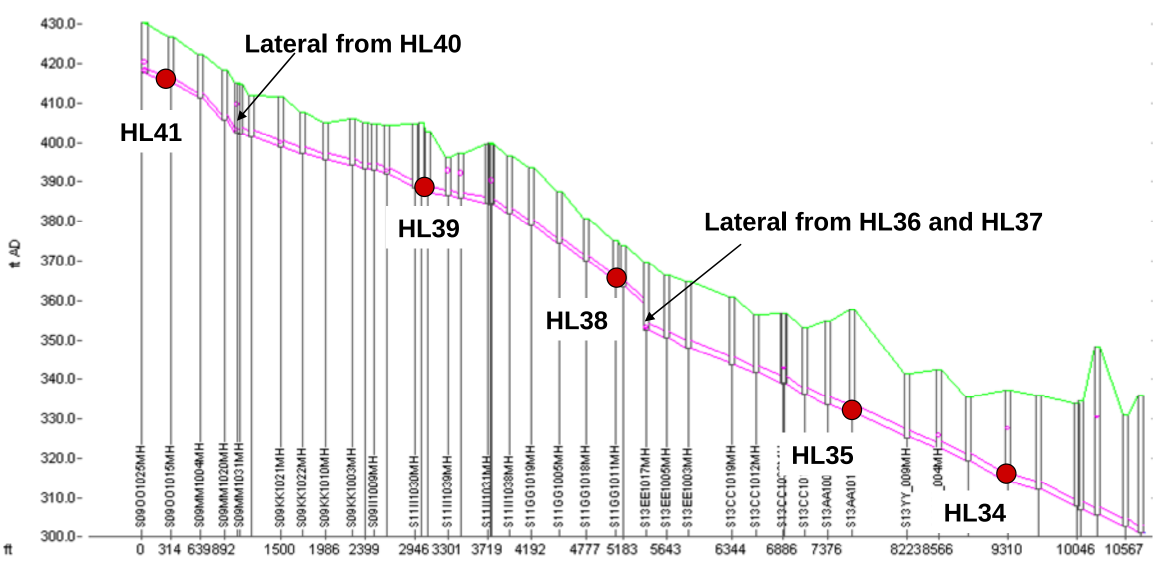


Figure 6-1. Profile of the Upper Gwynns Run Interceptor (GRI)

Group B: Downstream Gwynns Run Interceptor basins (HL25 – HL33)

As seen in Figure 6-2, the lower GRI has little slope from HL34 to the downstream of HL31, which caused frequent overflows directly downstream of HL31. After SC-812 construction, however, there has been no overflow event at this location. Another slope-limited section is between HL25 and HL26. Due to the rapid slope changes and possibly due to pipe blockage with sediment/debris, the DWF velocity decreases from 6 feet per second (ft/s) to 1 ft/s from HL28 to HL26.

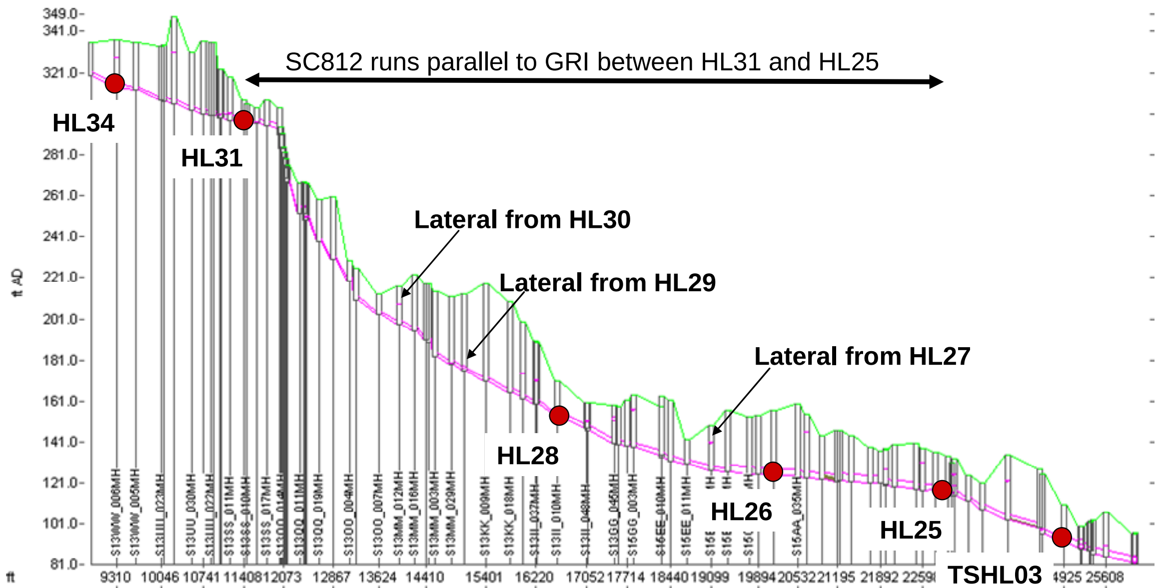


Figure 6-2. Profile of Lower GRI

Group C: Second Gwynns Run Interceptor and TSHL03 (HL20-HL24, TSHL03)

Dry weather velocity varied from 1 ft/s at HL22 to almost 9 ft/s at HL20 due to significant variations in the interceptor slope (Figure 6-3). However, simulation results showed that the velocity varied between 3 ft/s at HL22 to 5 ft/s at HL20. Field data were available to accurately represent the nearby pipe sizes and slopes; therefore, the appropriate DWF parameters were not adjusted for this section. Overall, the comparison revealed good correlation between the modeled and monitored data.

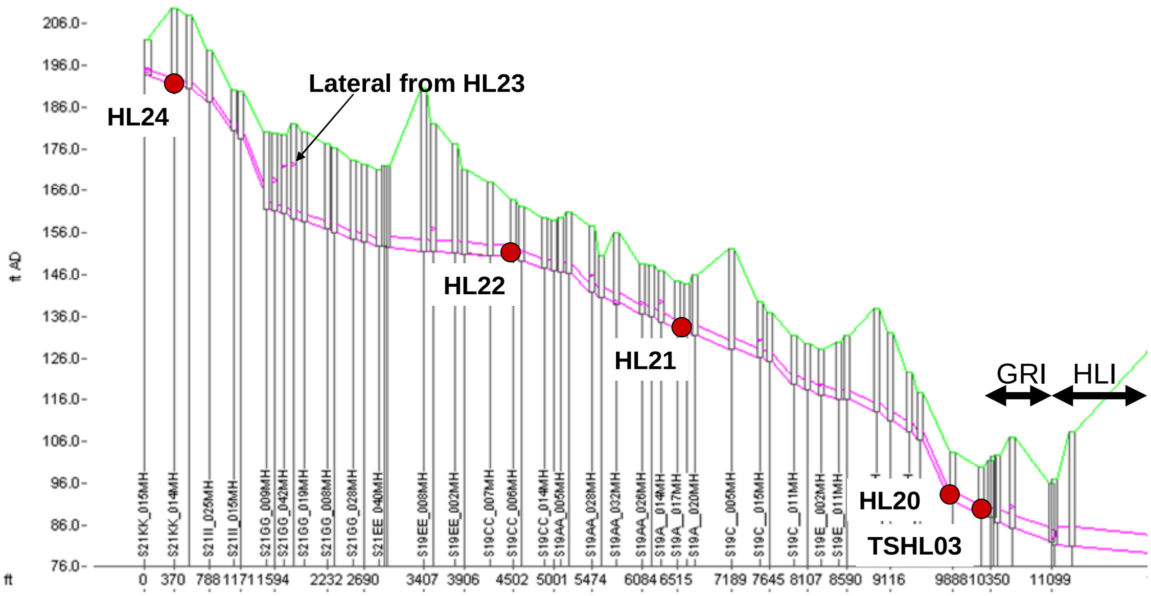


Figure 6-3. Profile of second Gwynns Run Interceptor (GRI)

Group D: Minor Flow Basins Contributing to HLI (HL15 – HL17, HL10 – HL13, HL06)

The CCTV records indicate that there were major sewer restrictions at downstream ends of HL13 and HL11 very close to the HLI. This could affect wet weather flow routing significantly, however, the DWF simulation results correlated well with monitored data.

Group E: Flow Basins along HLI (HL19, HL18, HL14, HL09A, HL09, HL08A, HL08, HL07, and TSHL01)

As shown in Figure 6-4, significant amounts of sediment accumulation could be seen in the HLI from midway between HL09A and HL09 (as shown by a brown line between the pipe invert and crown). This makes the HLI nearly ¾ full or more even during dry period (e.g. 72" of water in a 95" pipe at HL08A). Availability of as-built drawings with profiles and measured sediment depths from sonar inspections resulted in high correlation between modeled and monitored flow, depth, and velocity data along the HLI.

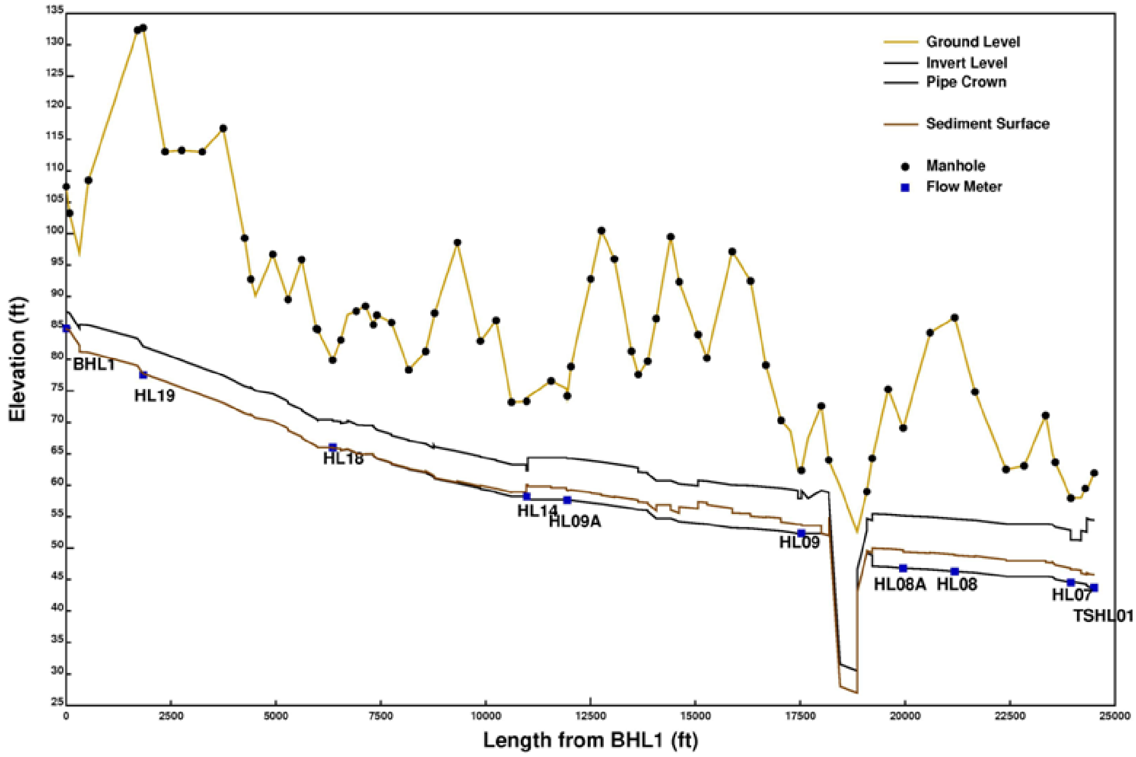


Figure 6-4. Profile of the High Level Interceptor (HLI) and accumulated sediment profile along the HLI

System-wide Flow Propagation Comparison:

Figures 6-5 and 6-6 review the average modeled flow (values shown outside of the parenthesis) versus average observed flow (values shown within brackets) during the August 11 – 22 and December 4 – 12 dry weather events in a schematic form. These figures exhibit flow progression from upstream to the downstream along with the appropriate boundary flows into the HLSS system. The boxes shown in blue indicate the meters used for calibration in flow rate, and the boundary meters in gray. Observed flow rates in Figure 6-5 showed that the GRI carried a flow less than 10 MGD, however significant flows were added to the HLI especially in the downstream portion of the HLI from several boundaries such as the Lower Jones Falls interceptor, and Jones Falls and Eastern Avenue force mains. At the downstream end of the HLI, the flow rate was approximately 75 MGD. It should be noted that another boundary flow had been added from the newly constructed Greenmount interceptor to the HLI right downstream of the flow meter HL08A since May 2008. This new flow rate would be approximately 2 MGD during dry weather and could be up to 15 MGD during peak wet weather events, which could worsen the existing capacity limitation in the downstream portion of HLI. This comparison revealed that there was not much difference in flow rate between summer and winter periods, and the simulated flow rate matched well with the observed data.

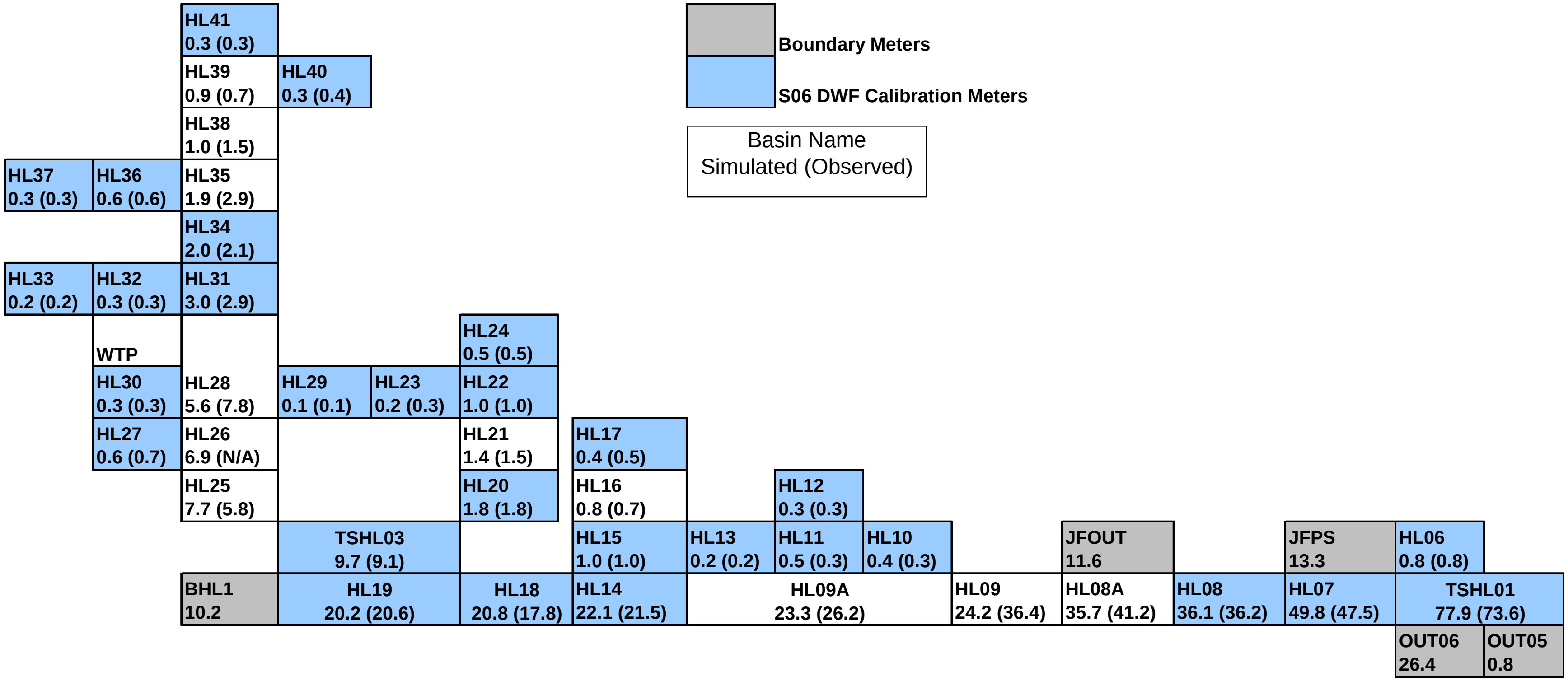


Figure 6-5. Modeled versus Observed for Average Dry Weather Flow for August 11 - 22

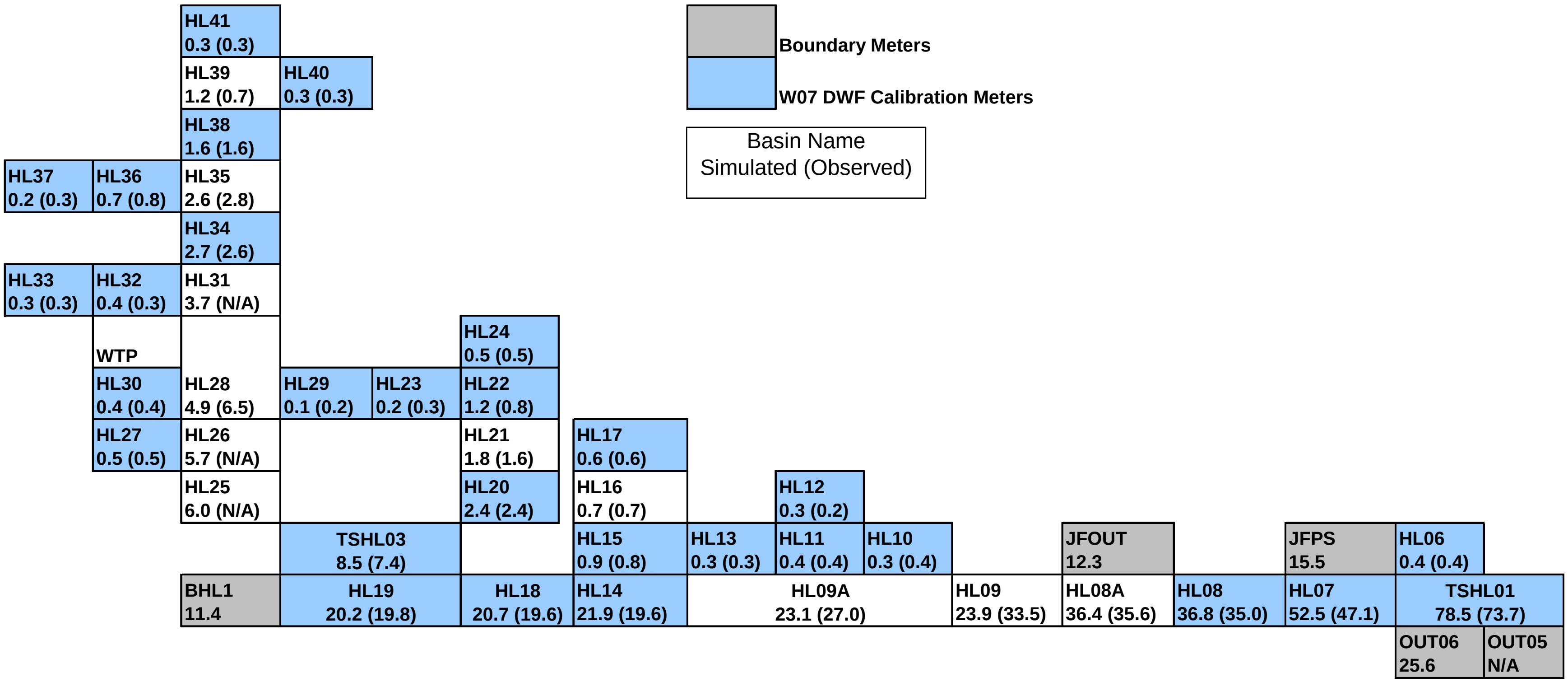


Figure 6-6. Modeled versus Observed for Average Dry Weather Flow for December 4 - 12

6.3 WET WEATHER CALIBRATION AND VALIDATION

6.3.1 Wet Weather Calibration Procedure

Calibration Event Selection:

As suggested in BaSES, all storms with 0.5 inches in volume or larger and pre-selected global storms by 1015 were considered for wet weather flow calibration. There were 29 global storms (Table 6-7) during the monitoring period, and the Radar data were provided for 24 of these global storms. Table 6-2 shows the 24 global storms used for wet weather flow calibration and InfoWorks model setup (configuration) that corresponds to each of these storms. Among the 24 storms, 12 storms were used for summer 06 calibration, seven storms were used for winter 07, and five were chosen for the post-SC812 calibration.

Table 6-2. Wet weather flow calibration events.

InfoWorks Network	Simulation start	Simulation End	Duration
Summer 06	5/10/2006	5/13/2006	4
Summer 06	6/1/2006	6/5/2006	5
Summer 06	6/18/2006	6/21/2006	4
Summer 06	6/24/2006	7/1/2006	7
Summer 06	7/4/2006	7/7/2006	4
Summer 06	7/21/2006	7/25/2006	5
Summer 06	8/31/2006	9/4/2006	5
Summer 06	9/4/2006	9/7/2006	4
Summer 06	9/13/2006	9/17/2006	5
Summer 06	9/27/2006	9/30/2006	4
Summer 06	10/4/2006	10/9/2006	6
Summer 06	10/16/2006	10/19/2006	4
Winter 07	10/26/2006	10/30/2006	5
Winter 07	11/6/2006	11/9/2006	4
Winter 07	11/15/2006	11/18/2006	4
Winter 07	11/21/2006	11/24/2006	4
Winter 07	12/21/2006	12/24/2006	4
Winter 07	12/30/2006	1/2/2007	4
Winter 07	1/6/2007	1/9/2007	4
Post SC812	2/28/2007	3/3/2007	4
Post SC812	3/14/2007	3/18/2007	5
Post SC812	4/3/2007	4/8/2007	6
Post SC812	4/10/2007	4/14/2007	5
Post SC812	4/13/2007	4/17/2007	5

Calibration Parameters:

Several parameters can be adjusted during wet weather flow calibration. Table 6-3 lists these parameters and summarizes how these parameters would be used for HLSS model calibration.

Table 6-3. Parameters for wet weather flow calibration, and their uses for HLSS model calibration.

Parameter	Use in Calibration
Capture coefficient	Capture coefficients were not used for adjustment since they were fixed during the process of resolving flow imbalance issues.
Depression storage	Fixed. Same as capture coefficient.
Catchment slope	Average slope was calculated in GIS for each subcatchment. Values were changed only if necessary.
Catchment width	Initial values calculated in GIS as Area divided by distance between catchemt centroid to sink. Values were changed for adjustment.
Runoff routing value	Used as a major calibration parameter

6.3.2 Input Data Quality and Model Parameter Sensitivity Checks

As a part of the wet weather model calibration process, the HLSS study team conducted several input data quality checks and calibration parameter sensitivity checks. This section describes findings from these checks.

Radar versus Rain Gauge Data

The quality of Radar data is very important to support wet weather flow calibration. Therefore, the HLSS team performed a random quality check on Radar data at or very near the point gauges. This exercise was conducted under the assumption that the rain gauge data were accurately recorded with no associated errors in measurements.

First, the Radar data was compared with those at rain gauges to assess the level of correlation. Sli/icer-processed Radar data from the nearest flow basins was compared with the rain gauge data (i.e., HL 40 with GR-09, HL30 with GR-07, and HL09 with JF-12 see Figure 6-7). These comparisons of rainfall depths are shown for the June 25, July 5, and November 16 storms for HL40 (Figure 6-8), HL30 (Figure 6-9), and HL09 (Figure 6-10), respectively. These comparison plots matched well in general, although some of the plots conveyed significant differences (e.g., June 25 storm at HL12).

Secondly, the Radar data was compared with flow data to check if any storm events exhibited inflow patterns that were inconsistent with Radar data. For example, inflows could be peaking at a different time or peaking at much higher rates in comparison to what could be expected only based on Radar data. As such, there was little correlation between rain and the corresponding flows in the system for the June 2 and June 25 storms. Figures 6-11 and 6-12 show the Radar and rain gauge hyetographs for the June 2 storm at HL 37 and HL33 respectively. The Radar data shows that the rain peak occurred at 8 PM with one inch of rainfall for half-an-hour, while the hydrograph exhibited almost no flow increase right after that. However, there was a small flow peak at around 11PM and this flow response was consistent with the rain gauge data. Therefore, Radar data for the June 2 storm would not be appropriate for model calibration.

Similarly, the Radar data for the June 25 storm did not correlate well with flow data for the sub-basins in the northern part of HLSS. Figures 6-13 and 6-14 show the Radar and rain gauge hyetographs for the June 25 storm at HL 41 and HL32, respectively. These hydrographs showed larger flow responses for the second rain peak (occurred the night of June 27) while the Radar data showed that there was very little rainfall on June 27.

These two storm's Radar data, however, were still considered for model calibration for two reasons: (a) this quality check process did not totally indicate that the Radar data was wrong, but needed to be supplemented by the point gauge data to achieve a better calibration, and (b) the June 25 storm was one of the major global storms that would be useful to 1015 for system-wide or regional model calibration.

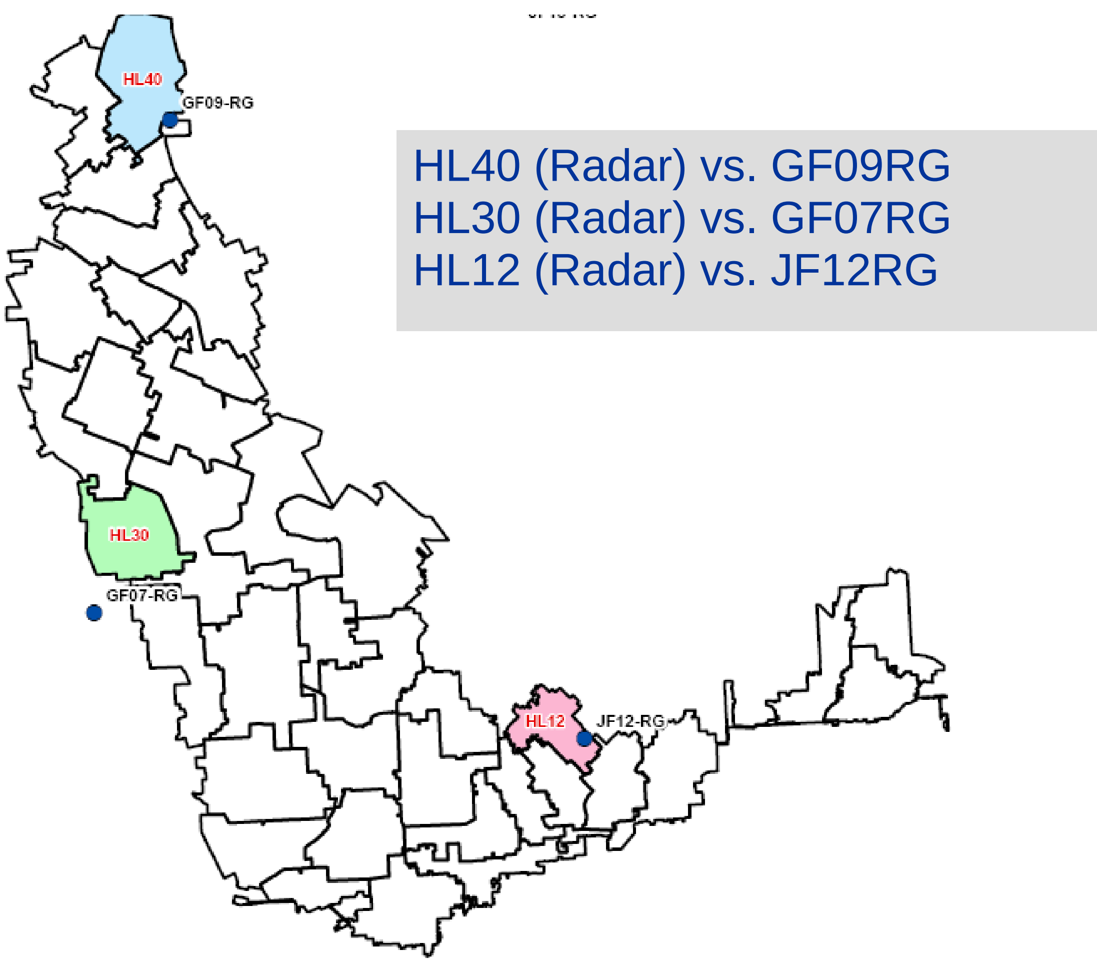


Figure 6-7. Radar vs. Rain gauge data at each point location

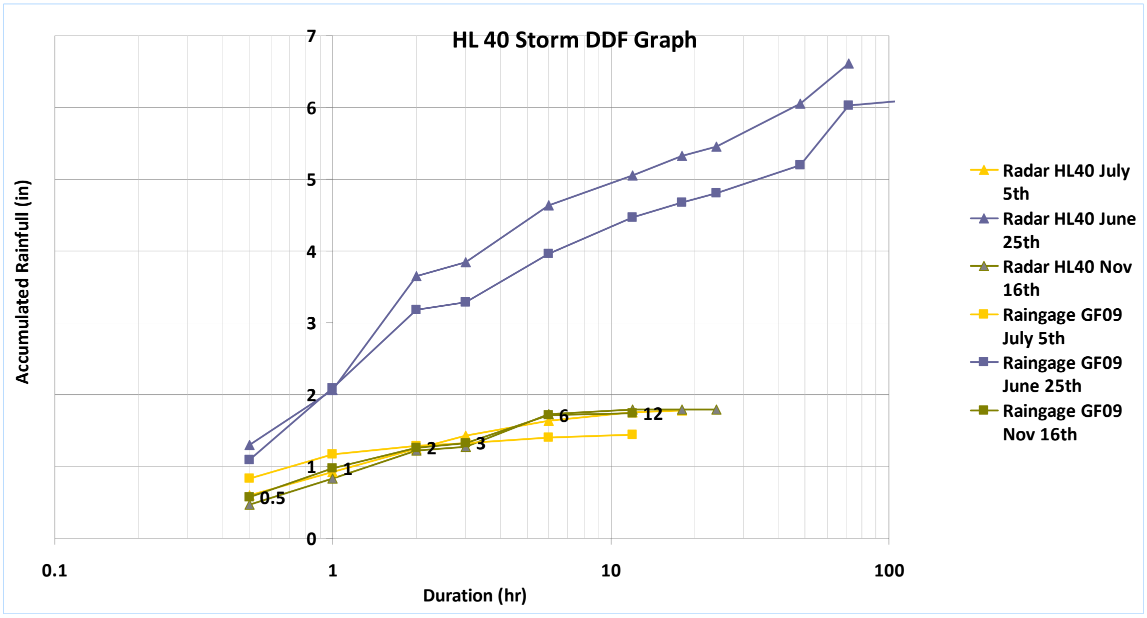


Figure 6-8. Radar (HL40) vs. Rain gauge (GF-09)

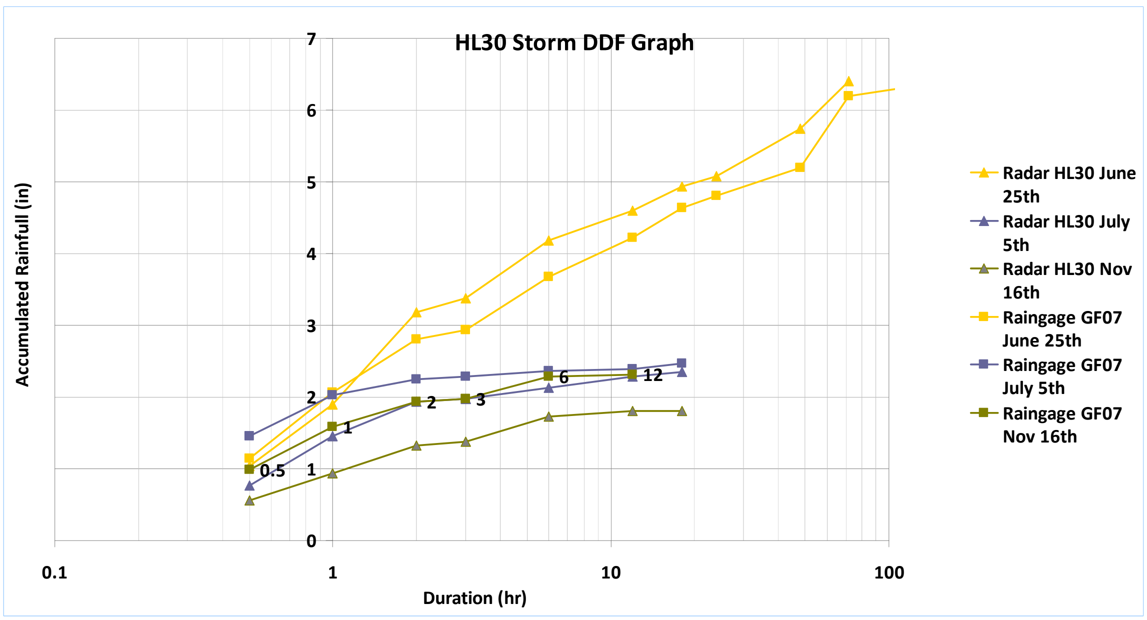


Figure 6-9. Radar (HL30) vs. Rain gauge (GF-07)

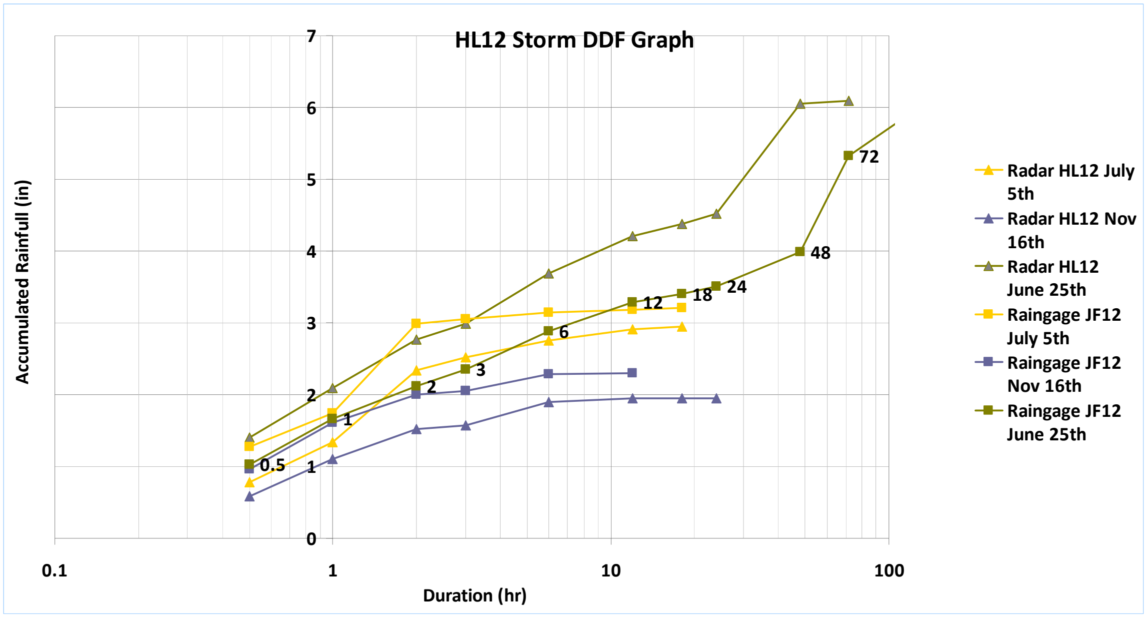


Figure 6-10. Radar (HL09) vs. Rain gauge (JF-12)

HL37, June 2nd storm

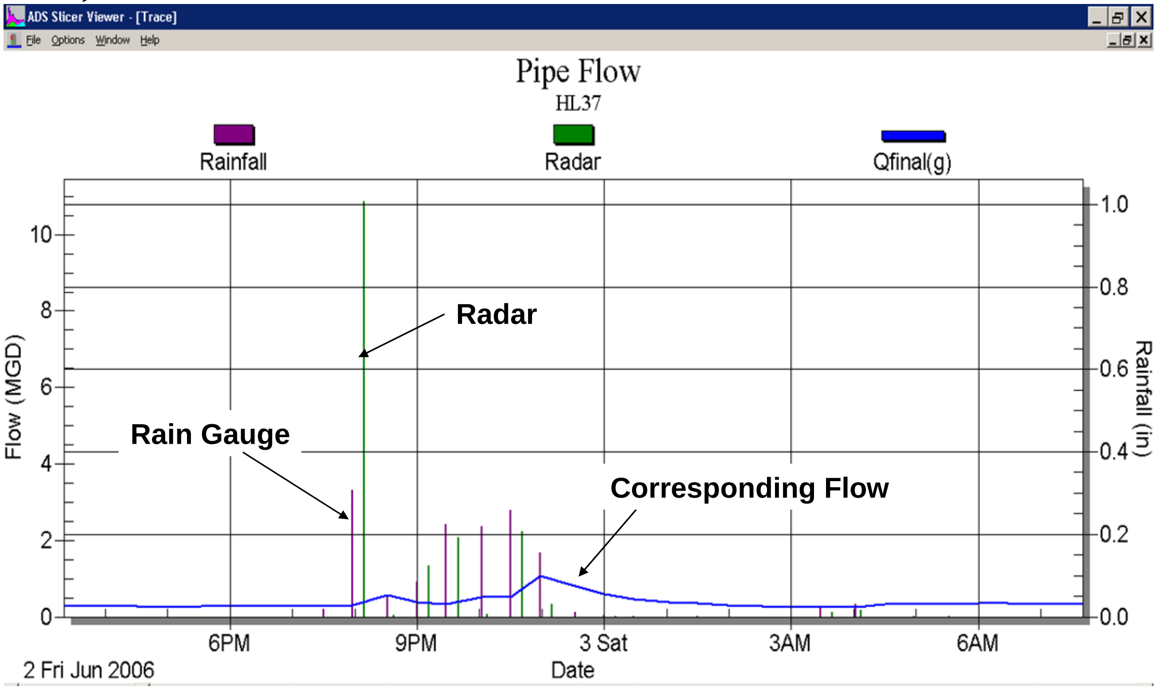


Figure 6-11. Radar vs. RG at HL37 for June 2 storm

HL33 June 2nd storm

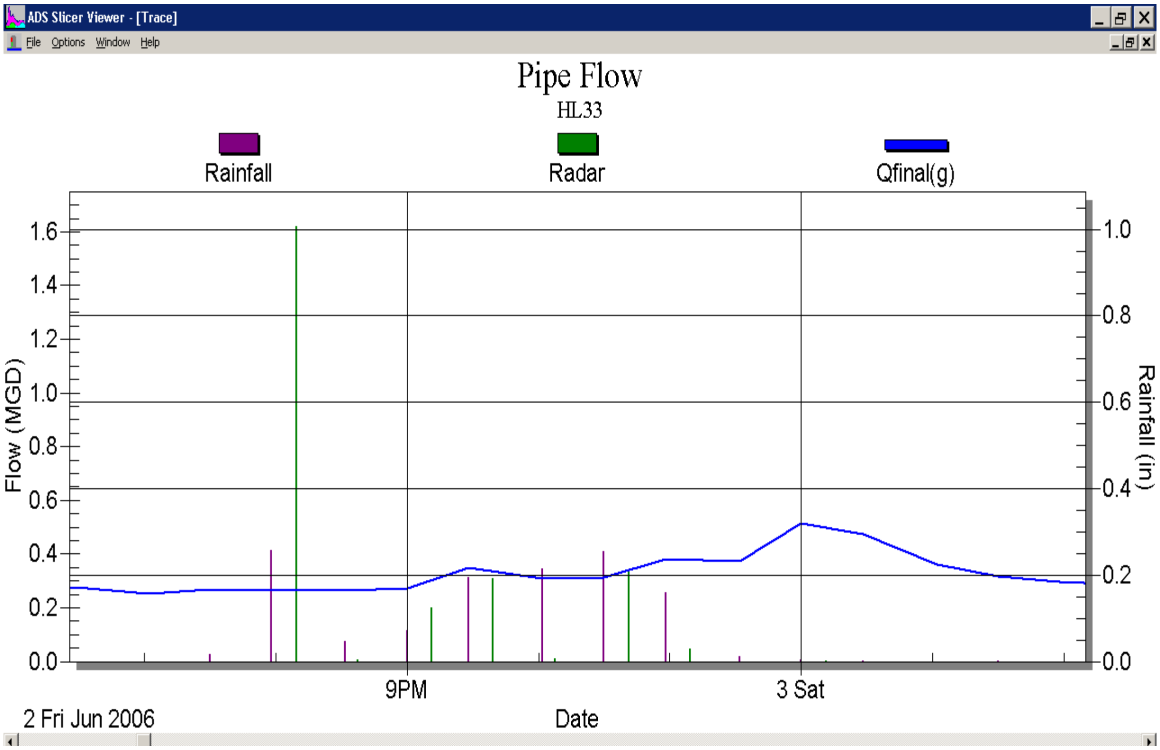


Figure 6-12. Radar vs. RG at HL33 for June 2 storm

June 25th storm – HL41

Figure 6-13. Radar vs. RG at HL41 for June 25 storm

June 25th – HL32

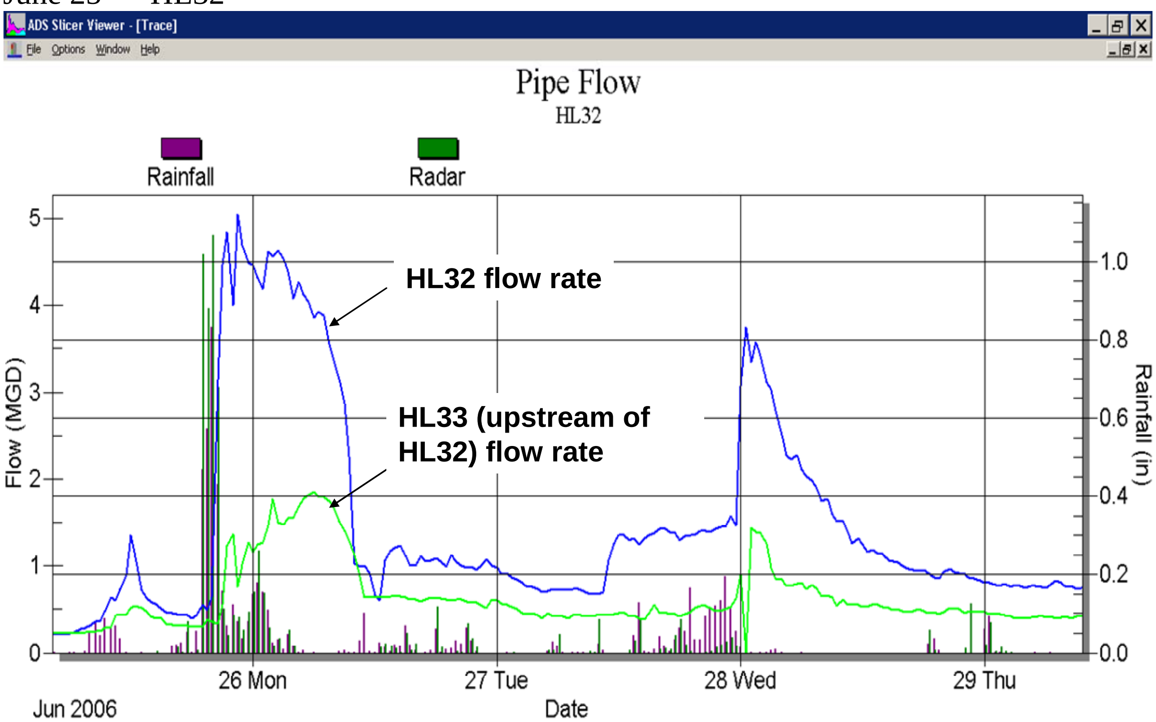


Figure 6-14. Radar vs. RG at HL32 for June 25 storm

Debris along HLI

Sediment depth determined using sonar technology was recorded every 50 ft along the HLI, however, sediment depth would need to be specified in InfoWorks as a single value for each pipe segment. Figure 6-15 shows the sediment profile for a HLI pipe segment between S35CC_005MH and S35AA_023MH. In this interceptor section, maximum sediment depth was 20” while the average sediment depth was 15”. To study whether maximum or average sediment depth is appropriate for model input, several sensitivity checks were conducted. Simulation results showed that maximum sediment depths sometimes overestimated the surcharge depths significantly (an example is shown in Figure 6-16). At flow meter HL18, simulation with maximum depths showed that there was severe surcharge associated with the November 7th storm, however, there was no real surcharge reported for that storm from field records. This condition was well represented by simulation using the average sediment depths and similar results were obtained from other sensitivity checks. Therefore, the average depth was applied for each pipe segment.

In HLI, there was severe debris accumulation determined using sonar inspections. Figure 6-17 and Figure 6-18 are the two major ones. Although they may work as a major flow restriction, this debris has yet to be incorporated into the model.

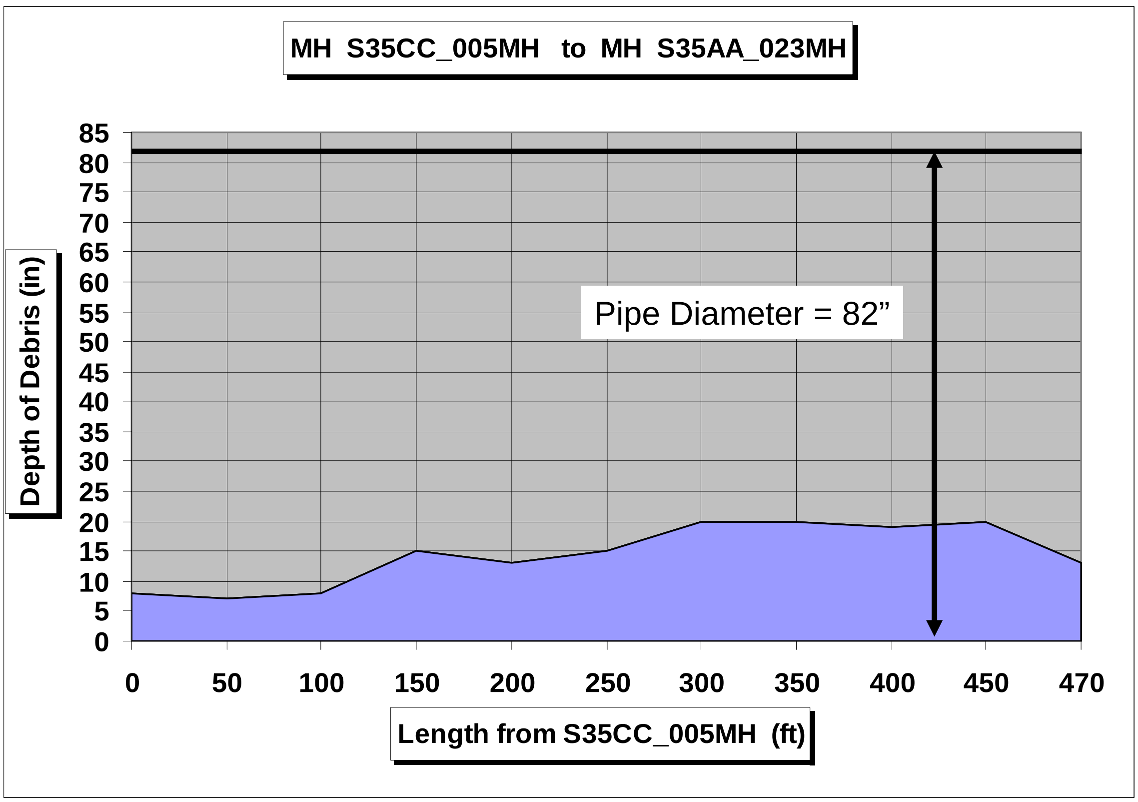


Figure 6-15. Sediment Profile from S35CC_005MH to S35AA_023MH

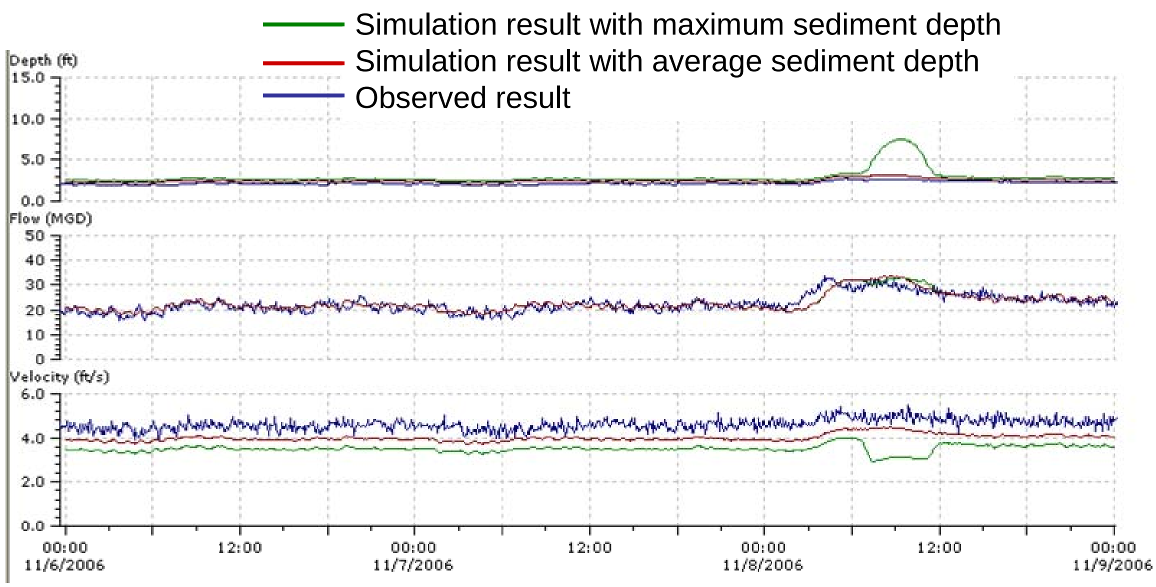


Figure 6-16. Sediment depth sensitivity results for November 7th storm at HL18 flow meter - one with maximum (green) and the other with average (red) depth.

Figure 6-17. Debris found between S33C__014MH and S33C__029MH

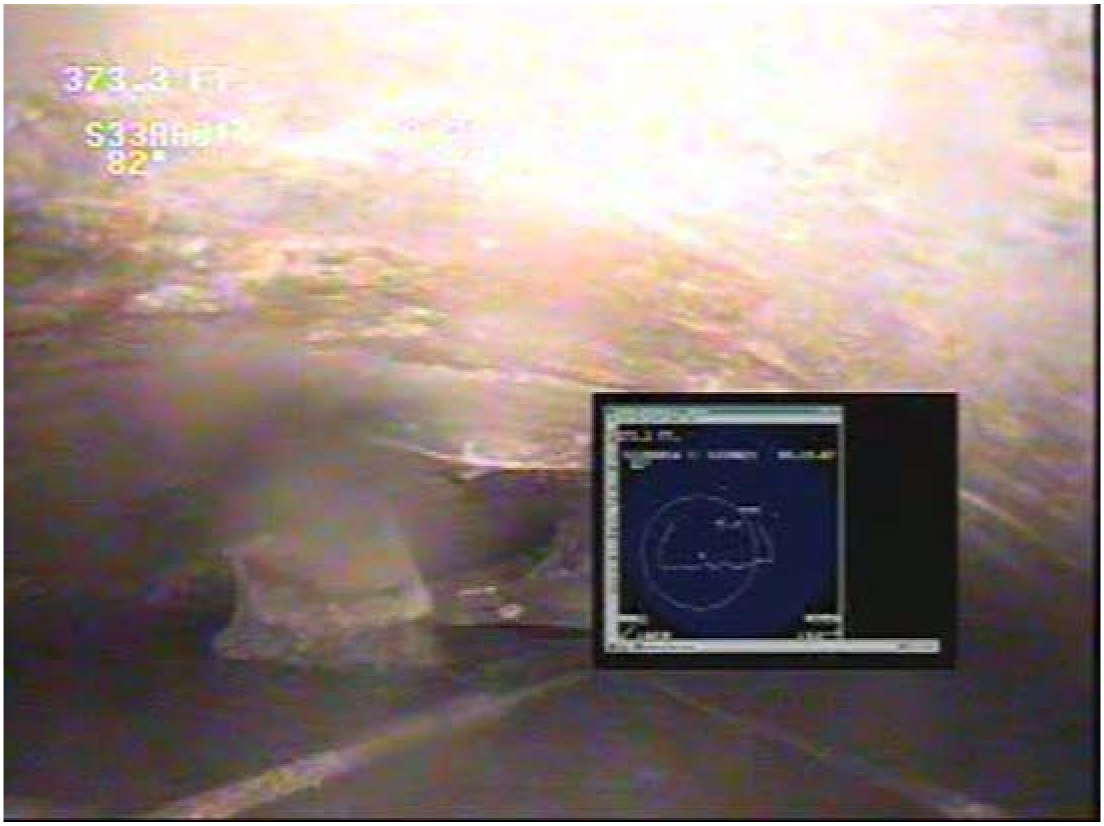


Figure 6-18. Debris found between S33A__021MH and S33AA_014MH

Capture Coefficients - Seasonal versus year-round

Another sensitivity analysis was conducted with three different capture coefficients – summer, winter, and year-round. The purpose of this analysis was to check if the simulated results with seasonal capture coefficient could better reproduce surcharge depths and peak flows than a year-round capture coefficient. This was conducted using the November 16 storm, one of the major winter storms observed during the primary monitoring period.

For the November 16th storm, the differences were prominent at HL33 and HL19. Wet weather calibration at HL33 is very important since there is an engineered SSO 132 still being active immediately upstream of the flow meter. Figure 6-19 shows surcharge depth and flow rate pattern were best estimated using the winter capture coefficient.

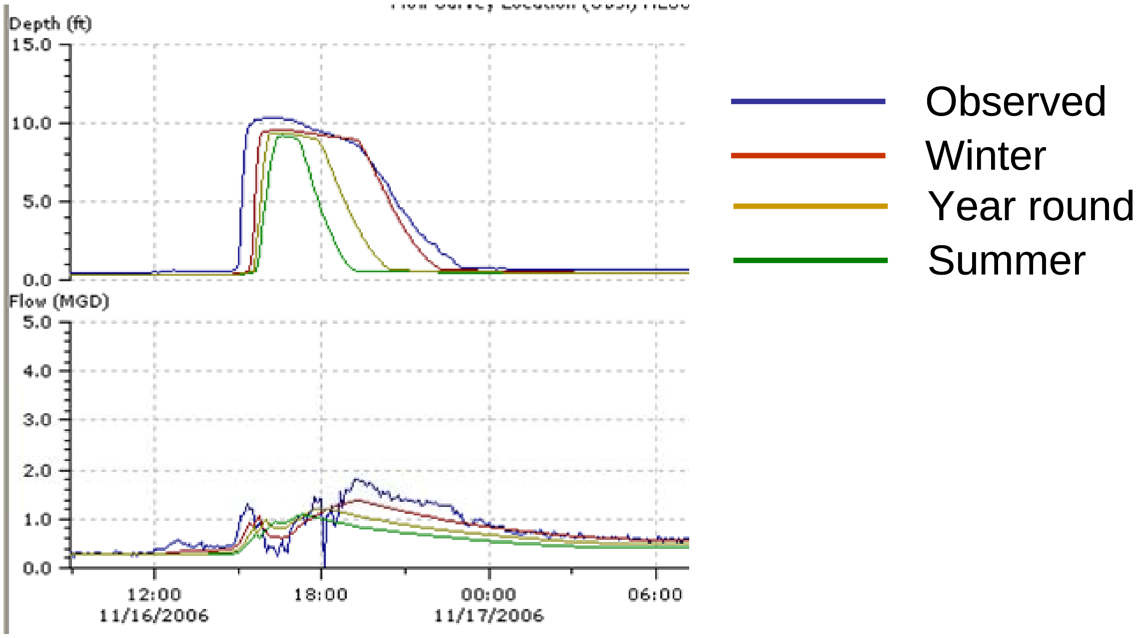


Figure 6-19. Sensitivity check with seasonal and year-round capture coefficient at HL33 for November 16 storm.

Figure 6-20 shows the depth, flow, and velocity comparisons of three different simulations with summer, winter and year-round capture coefficients with the observed data at HL19. HL19 is a flow meter located approximately 1,500 ft downstream of the inflow point of GRI. This showed that the simulation with winter capture coefficient best reproduced the surcharge. It should be noted that the flow data was time-shifted backwards by an hour, so the rising rim of the hydrograph with winter capture coefficient matched very well with observed data.

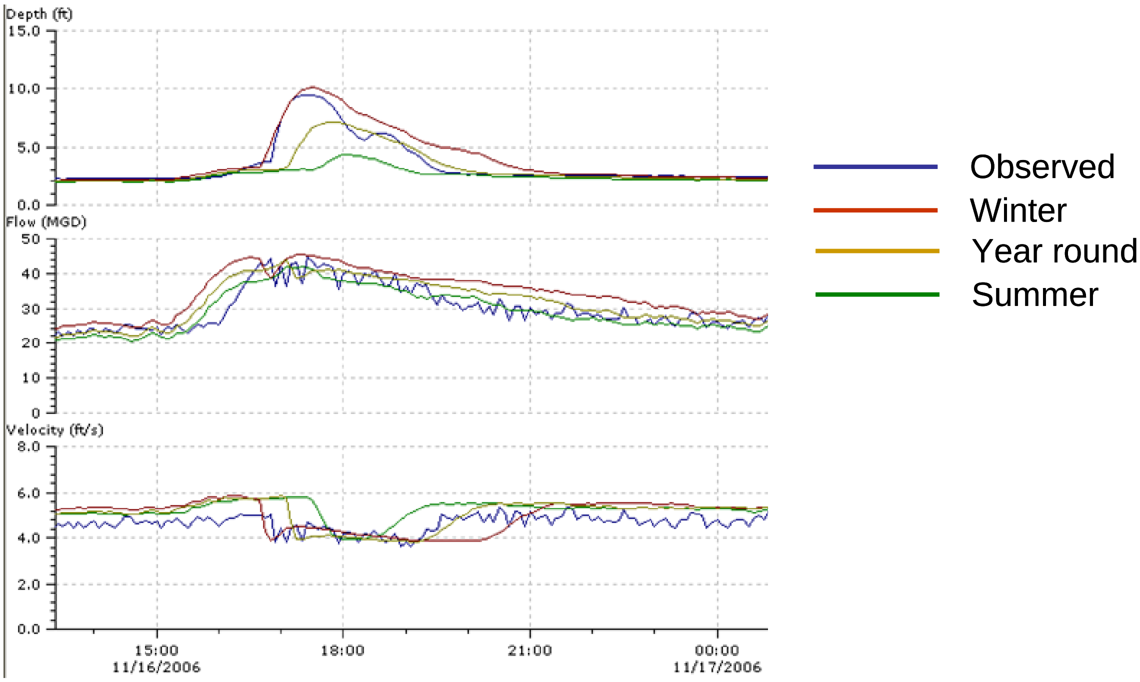


Figure 6-20. Sensitivity check with seasonal and year-round capture coefficient at HL19 for November 16th storm.

6.3.3 Wet Weather Calibration Evaluation

The adequacy of wet weather flow (WWF) calibration was evaluated in two ways. First, simulated depth, flow, and velocity were compared with observed for each global storm using time-series plots. Next, the simulated results were compared with observed in terms of peak flow, flow volume, and peak surcharge depth using regression plots.

The WWF time-series comparisons for all the flow meter locations are shown in Appendix 2-A for summer 2006 storms and in Appendix 2-B for the winter 2007 and post-SC812 storms. The regression plots for all season storms are shown in Appendix 3. With these plots, the simulation results were reviewed and discussed here for each group in HLSS, which are similar to the DWF comparisons:

A. Upper Gwynns Run Interceptor basins (HL34 – HL41)
B. Lower Gwynns Run Interceptor basins (HL25 – HL33)
C. Second Gwynns Run Interceptor and TSHL03 (HL20-HL24, TSHL03)
D. Minor flow basins contributing to HLI (HL15 – HL17, HL10 – HL13, HL06)
E. Flow basins along HLI (HL19, HL18, HL14, HL09A, HL09, HL08A, HL08, HL07, and TSHL01)

Group A: Upper Gwynns Run Interceptor basins (HL34 – HL41):

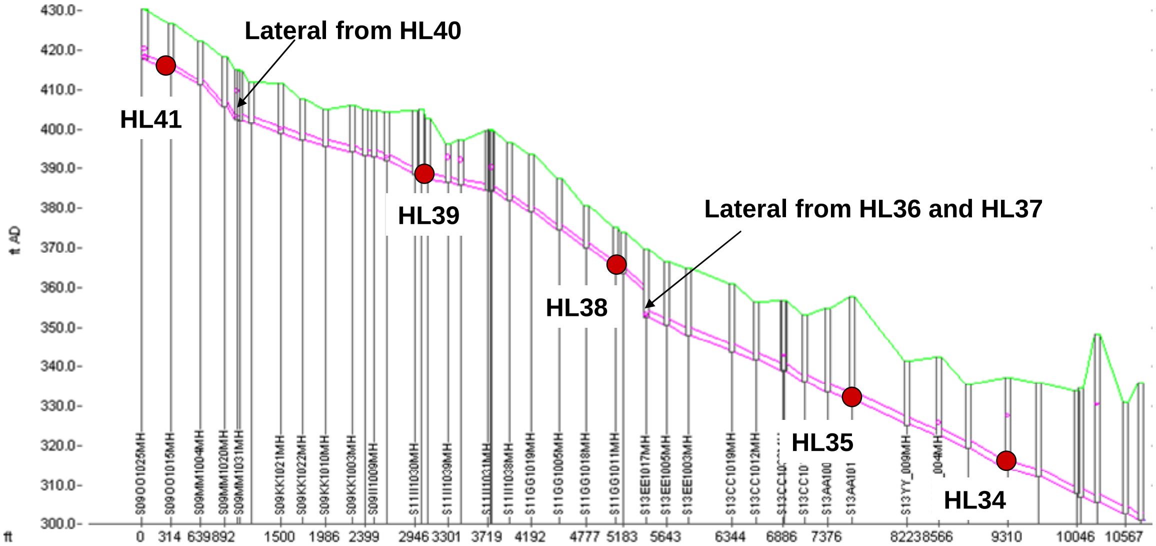


Figure 6-21. Profile of the Upper Gwynns Run Interceptor (GRI)

Flow basins in group A had relatively high capture coefficients both in summer and winter in comparison to other HLSS basins. The large volume of RDII resulted in frequent surcharges along the GRI and this would be important from two aspects. First of all, in the GRI from middle of HL41 basin to the HL31 flow meter, some pipes in HL37 and HL36 basins were cleaned and relined in the SC-807 and SC-831 projects. Therefore, any surcharge along these relined pipes might be due to capacity limitation. Secondly, there were several engineered SSOs in these basins and some of them experienced overflows during storm events that alleviated SSOs along the GRI. Since most of these engineered SSOs have been eliminated, the risk of SSOs has actually increased especially along the GRI.

Table 6-4 shows the evaluation summary for peak flow, volume, and peak surcharge depths at locations in this group. Very sharp inflows were observed for a very short duration at some flow meter locations such as the November 16 storm at HL37, and the July 5 and December 22 storms at HL40. These inflows resulted in a slightly moderated, yet peaky flow response in downstream flow meters such as HL38 and HL39. However, these sharp inflows were not modeled since those are event specific and the volume is not significant.

Group B: Lower Gwynns Run Interceptor basins (HL25 – HL33):

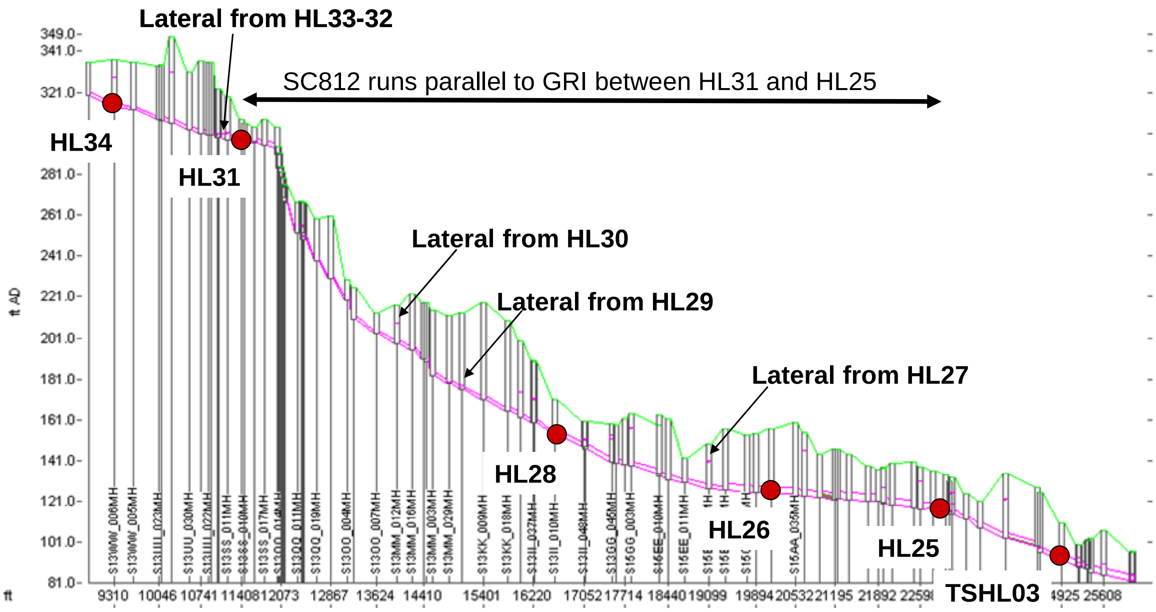


Figure 6-22. Profile of the Lower Gwynns Run Interceptor (GRI)

A general evaluation of calibration results is summarized in Table 6-9. For the group B region, calibration results were further evaluated at the following key locations.

- *Liberty Heights Avenue:*

Since there are three active engineered SSOs near HL32 and HL33, the hydraulic model should be able to simulate the surcharge conditions properly so that the model could be used for evaluation of the potential impacts associated with the elimination of these engineered SSOs. Simulated peak flows and volumes matched very well with observed data at HL33, while simulated peak flow and peak depth were underestimated at HL32. This is most likely due to an erroneous representation of engineered SSO 134 in the model.

Since the overflow pipe invert was only 1 foot above the manhole invert, a significant amount of flow was sent towards the overflow pipe in the simulation. However, based on the hydrograph and peak depth graph at HL32, the overflow pipe probably has some unknown flow restrictions such as a heavy flap valve on the other side of the pipe. This engineered SSO 134 issue will be addressed in the final model refinement.

- *2800 Dukeland Street*:

Historically, there have been many SSO's at this location, therefore, the HLSS team wanted to ensure that the surcharge and SSOs were well estimated for summer 2006 and winter 2007. Although the peak depth was underestimated at HL31 directly upstream of the SSO points, simulation results were able to reproduce SSOs at the location.

- *Downstream end of SC812:*

SC-812 was shortened by the City at its downstream end from its original design due to budget constraints. It connects to the existing 32" GRI directly downstream of HL25, but was initially designed to connect to the HLI directly. Figure 6-23 is a scatter graph at HL812C, one of the four flow meters setup to evaluate potential improvements from the SC812 relief pipe, and is located directly upstream of where SC-812 joins the existing GRI. The scatter graph showed that the existing 32" pipe was frequently surcharged by more than 10 feet, which was worse than the surcharge at the same location before SC-812 was put in service.

The current model does not reproduce surcharge along the downstream portion of the GRI, however, this would be improved once any CCTV data that can confirm any significant blockage is incorporated.

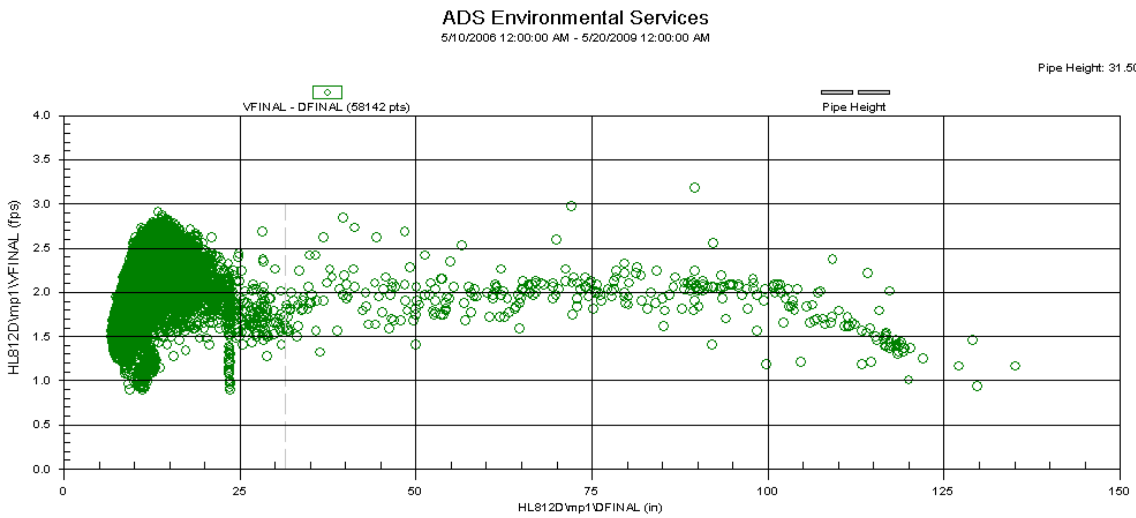


Figure 6-23. Frequent surcharge at HL25 after SC-812 was put in service

Group C: Second Gwynns Run Interceptor and TSHL03 (HL20-HL24, TSHL03):

The sewer in this group has a sufficient downward slope from HL24 to HL20, so it has rarely surcharged even though the basin capture coefficients were relatively high. Table 6-9 shows evaluation summary for peak flow, volume, and peak surcharge depth.

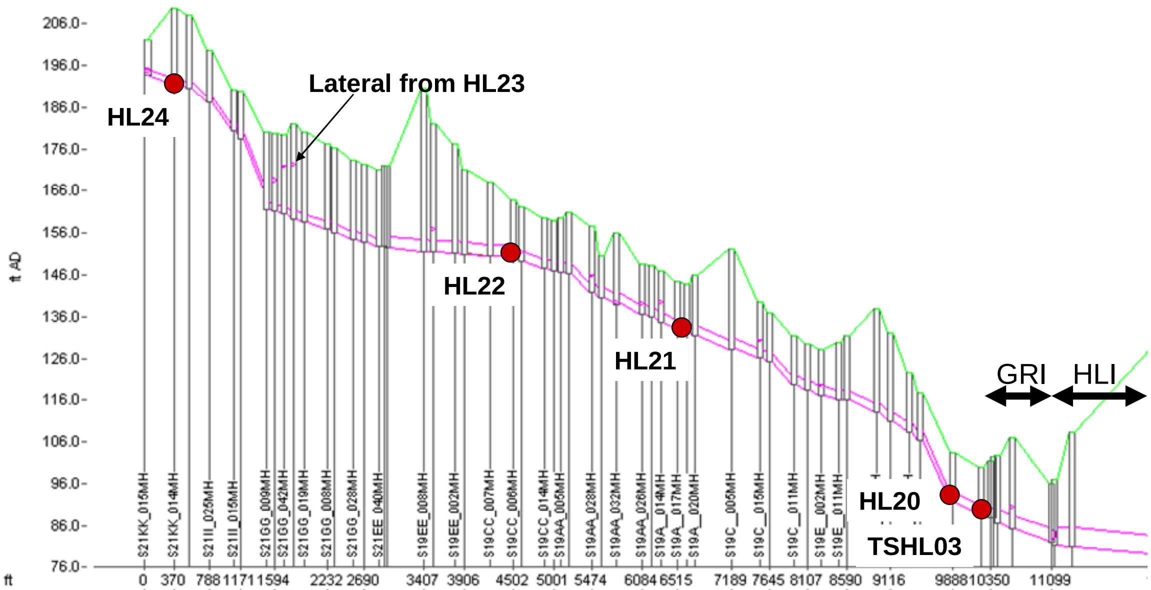


Figure 6-24. Profile of the Lower Gwynns Run Interceptor (GRI)

Group D: Minor flow basins contributing to HLI (HL15 – HL17, HL10 – HL13, HL06):

A general evaluation of the calibration results is summarized in Table 6-9. For meters in group D, calibration results were further evaluated at the following key locations.

- *Inverted siphon at HL16*

There is an inverted siphon directly downstream of the HL16 flow meter. It is approximately 250' long and is 20" in diameter. The pipe at HL16 has frequently surcharged and this may be due to the siphon's capacity limitation. Surcharge at HL16 was slightly underestimated although 8" of sediment accumulation was assumed for the siphon. The nearby manholes had depths from approximately 12-18 ft, which were a few feet higher than the maximum surcharge depth of seven feet. However, further investigation of the siphon is suggested since the surcharge may worsen if the siphon capacity diminishes over time.

- *Flow Back-up from HLI*

The surcharge depth graphs showed that there were frequent flow back-up from the HLI at flow meters adjacent to the HLI, namely, HL06, HL10, HL11, and HL13. Surcharge due to the HLI back-up was up to 10 feet that could potentially induce SSOs at low ground-elevation manholes adjacent to HLI. Calibration results showed that the surcharge depths at these meters were estimated very well. The HLI surcharge could result from limitations in the interceptor capacity as well as the additional flow from incoming lateral pipes.

Group E: Flow Basins along HLI (HL19, HL18, HL14, HL09A, HL09, HL08A, HL08, HL07, and TSHL01):

As shown in Table 6-4, surcharge depth and flow were well estimated along the HLI due to two reasons: sediment depths from sonar inspection from HL18 to TSHL01 and the availability of as-built drawings with sewer profiles for most sections along the HLI. The as-built drawings provided pipe diameter, shape, and detailed information about lateral pipe connections. Those were very useful for model development since the pipe size and invert depth measurement from field surveys were unreliable due to heavy silt accumulation in the HLI. Surcharges and SSOs along the HLI are further discussed in the following model validation section.

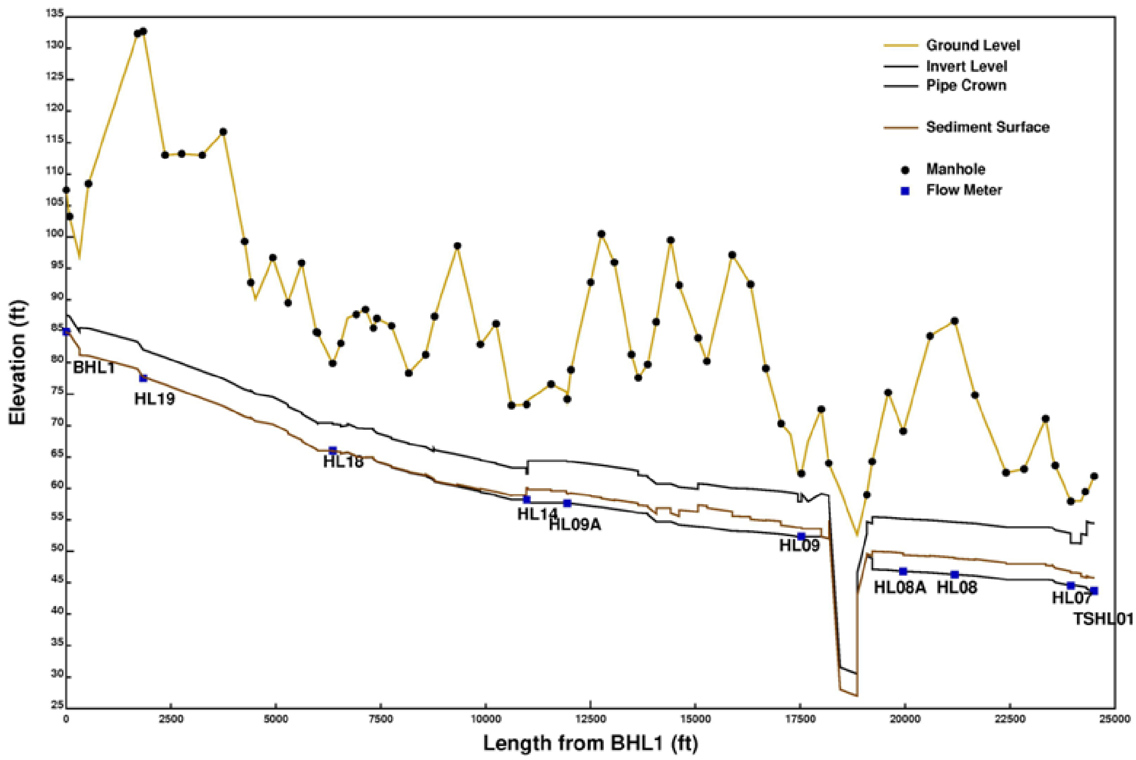


Figure 6-25. Profile of the High level Interceptor (HLI) and accumulated sediment profile

Table 6-4. Wet weather flow calibration evaluation						
Group A Meters	Peak Flow		Volume		Peak Depth	
	Summer	Winter	Summer	Winter	Summer	Winter
HL41	G	G	G	G	**N/A (Hardly Surcharged)**	**N/A (Hardly Surcharged)**
HL40	G	**U (instant inflows)**	G	G	**N/A (Hardly Surcharged)**	**N/A (Hardly Surcharged)**
HL39	G	**U (instant inflows)**	G	G	G	G
HL38	G	G	G	G	**N/A (Not many surcharge data available)**	**N/A (Not many surcharge data available)**
HL37	G	G	G	G	**N/A (Hardly Surcharged)**	**N/A (Hardly Surcharged)**
HL36	G	**N/A (Not many data available)**	G	**N/A (Not many data available)**	**N/A (Hardly Surcharged)**	**N/A (Hardly Surcharged)**
HL35	G	G	G	G	G	G
HL34	G	**U (question in engineered SSO 130)**	G	G	G	G

Group B Meters	Peak Flow		Volume		Peak Depth	
	Summer	Winter	Summer	Winter	Summer	Winter
HL33	G	G	G	G	G	G
HL32	G	**U (question in engineered SSO 134)**	G	G	G	**U (question in engineered SSO 134)**
HL31	G	**N/A (meter eliminated)**	G	**N/A (meter eliminated)**	**U (question in engineered SSO 130)**	**N/A (meter eliminated)**
HL30	G	G	G	G	**N/A (sewer hardly surcharged)**	**N/A (sewer hardly surcharged)**
HL29	G	G	G	G	**N/A (sewer hardly surcharged)**	**N/A (sewer hardly surcharged)**
HL28	G	G	G	G	**U (check sonar once available)**	**U (check sonar once available)**

Table 6-4. Wet weather flow calibration evaluation

HL27	G	G	G	G	**U (instant inflows)**	**U (instant inflows)**
HL26	G	G	G	G	**U (check sonar once available)**	**U (check sonar once available)**
HL25	G	G	G	G	G	G

Group C Meters	Peak Flow		Volume		Peak Depth	
	Summer	Winter	Summer	Winter	Summer	Winter
HL24	G	G	G	G	**N/A (sewer hardly surcharged)**	**N/A (sewer hardly surcharged)**
HL23	G	G	G	G	**N/A (sewer hardly surcharged)**	**N/A (sewer hardly surcharged)**
HL22	G	G	G	G	**N/A (sewer hardly surcharged)**	**N/A (sewer hardly surcharged)**
HL21	G	G	G	G	**N/A (sewer hardly surcharged)**	**N/A (sewer hardly surcharged)**
HL20	G	G	G	G	G	G
TSHL03	G	G	G	G	G	G

Group D Meters	Peak Flow		Volume		Peak Depth	
	Summer	Winter	Summer	Winter	Summer	Winter
HL17	G	G	G	G	**N/A (sewer hardly surcharged)**	**N/A (sewer hardly surcharged)**
HL16	G	G	G	G	**U (inverted siphon may have sediment)**	**U (inverted siphon may have sediment)**
HL15	G	G	G	G	G	G
HL14	G	G	G	G	G	G
HL13	G	G	G	G	**N/A (sewer hardly surcharged)**	**N/A (sewer hardly surcharged)**
HL12	**U (instant inflows)**	**U (instant inflows)**	G	G	G	G
HL11	G	G	G	G	G	G
HL10	**U (instant inflows)**	**U (instant inflows)**	G	G	G	G

Table 6-4. Wet weather flow calibration evaluation						
HL06	G	G	**O (short term DWF fluctuation)**	G	G	G

Group E Meters	Peak Flow		Volume		Peak Depth	
	Summer	Winter	Summer	Winter	Summer	Winter
HL19	G	G	G	G	G	G
HL18	G	G	G	G	**U (missed July 5th and Sep. 5th surcharges)**	G
HL09A	G	G	G	G	G	G
HL09	**N/A (bad meter)**	**N/A (bad meter)**	**N/A (bad meter)**	**N/A (bad meter)**	G	G
HL08A	G	G	G	G	G	G
HL08	G	G	G	G	G	G
HL07	G	G	G	G	G	G
TSHL01	G	G	G	G	G	G

6.3.4 Wet Weather Calibration/Validation

The adequacy of wet weather calibration was assessed using two approaches. First, the simulated maximum hydraulic grade line (HGL) was compared with the observed maximum surcharge depth at a series of flow meters along the HLI where the sewer had frequently surcharged during severe storm events. Two major storms, July 5 and November 16, that occurred during the primary flow monitoring period in summer and winter were used for HGL comparison. Similar analysis would be conducted for the GRI once the CCTV/sonar data was available for the Lower GRI to enhance model calibration. Secondly, the simulated lost volumes from engineered and other SSO locations were obtained from the November 16 simulation and the locations/corresponding overflow volumes were compared with the known and engineered SSO locations. This process was used to check the adequacy of model calibration from an SSO standpoint.

Model Validation along HLI with Maximum HGL:

- *HLI for the July 5 Storm*

Figure 6-26 shows the maximum simulated HGL comparison with observed data at each flow meter on the HLI for the July 5 storm. There was no observed peak depth available at TSHL01 due to meter malfunctioning during the peak surcharge. The observed data showed that the HGL dropped sharply between HL14 and HL09A. It is unlikely that the depth data at HL09A would drop so sharply, so we assumed that this data quality was questionable. The maximum HGL was simulated very well from HL09 and downstream, while it was underestimated for the upper portion of the HLI. This severe surcharge for the upper portion of HLI might be due to flow restriction caused by debris found by sonar inspection near S33C_029MH and S33AA_014MH (Figure 6-26). This debris might be working as a bottle neck during the peak flow times of the interceptor. This, in turn, may be the reason for severe surcharging of the upstream portion of the siphon.

- *HLI for the November 16 Storm*

Figure 6-27 shows the maximum simulated HGL comparison with observed data at each flow meter on the HLI for the November 16 storm. The simulated maximum HGL matched the observed for the whole HLI. As shown, there were at least 5 manholes where the maximum HGL exceeded the manhole rim elevation and became an SSO, or nearly reached the manhole rim elevation, which has SSO potential. At the BCDC manhole directly downstream of the inverted siphon, manhole rim was below the maximum HGL, implying that there was a SSO event in front of BCDC on November 16, 2006.

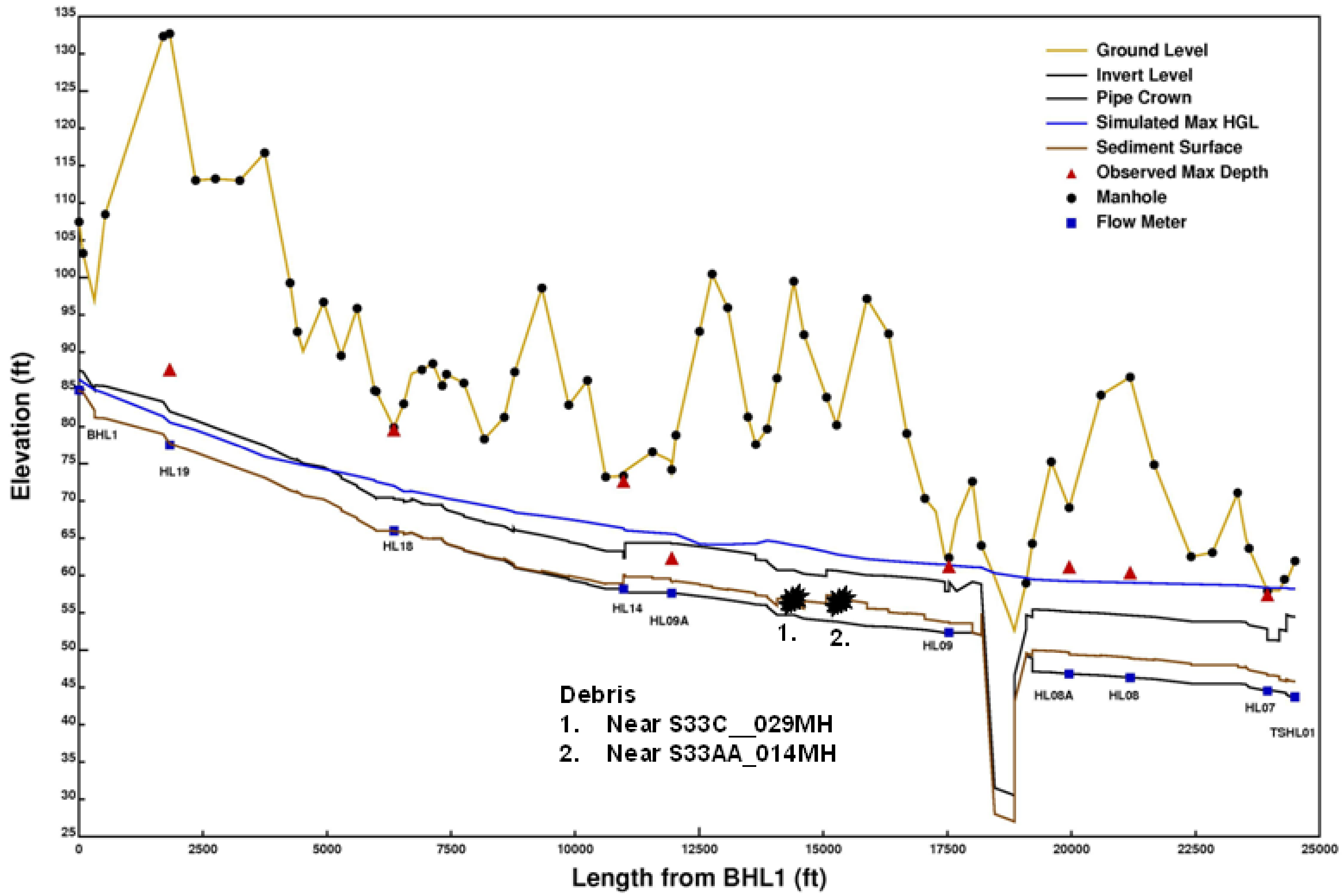


Figure 6-26. Simulated and observed maximum HGL along HLI for July 5th storm

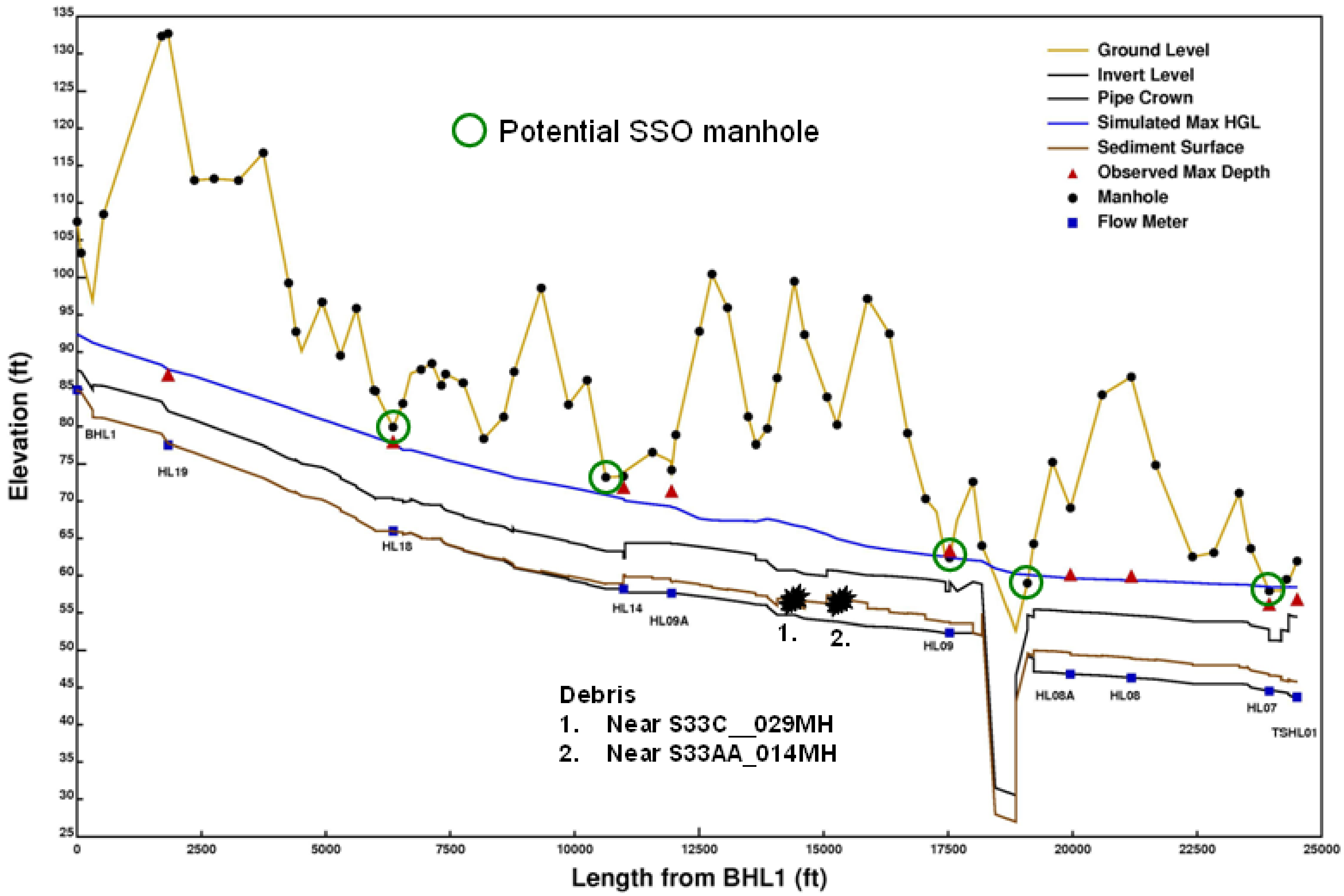


Figure 6-27. Simulated and observed maximum HGL along HLI for November 16th storm

The maximum HGL analysis performed in this model validation process strongly indicates that the high surcharge of the HLI was resulting from the high water depth boundary condition at the end of the HLI. A high HGL level at TSHL01 would indicate a flow back up from the outfall interceptor. However, an integrated HLI and outfall interceptor study to be performed by the City on a regional-scale would provide strong technical basis for mitigation of SSOs in this area.

Model Validation with Engineered SSO data and SSO records

Engineered SSO:

There were 12 active engineered SSO locations in HLSS during the primary flow monitoring period. Table 6-5 shows the calculated peak flow rate and lost volumes through these locations for the November 16 storm, and the specific locations where the model predicted water loss are shown in Figure 6-28. Simulation results revealed that there was approximately 1.2 million gallons of water loss from the entire system through engineered SSOs.

Table 6-5 also indicates whether there were any overflows at these locations during the Paragraph 8 flow monitoring period from 2003 to 2007. The evidence of overflows are shown in Figure 6-29 and 6-30 in scatter graphs. The simulated overflow locations for the November 16 storm matched very well with the engineered SSOs that exhibited overflow evidence between 2003 and 2007. This comparison was used for confirming model adequacy based on past monitoring data.

Table 6-5. Lost volume and peak flow through engineered SSO

Engineered SSO ID	Peak Flow (MGD)	Volume lost (gal)	Any overflow between 03 to 06?
130	3.42	392,230	Yes
57	1.77	227,970	Yes
107	2.74	166,320	Data not available
55	1.85	128,510	Yes
132	1.28	95,260	Yes**
56	0.71	71,120	Yes
131	0.84	55,680	Yes
134	0.50	55,640	Yes*
126	0.33	16,180	Yes
128	0.00	0	No
135	0.00	0	Data not available
106	0.00	0	Data not available
Total (gal)		1,208,910	

* see scatterplot in Figure 4-14 for overflow on Nov. 16th

** see scatterplot in Figure 4-15 for overflow on Nov. 16th

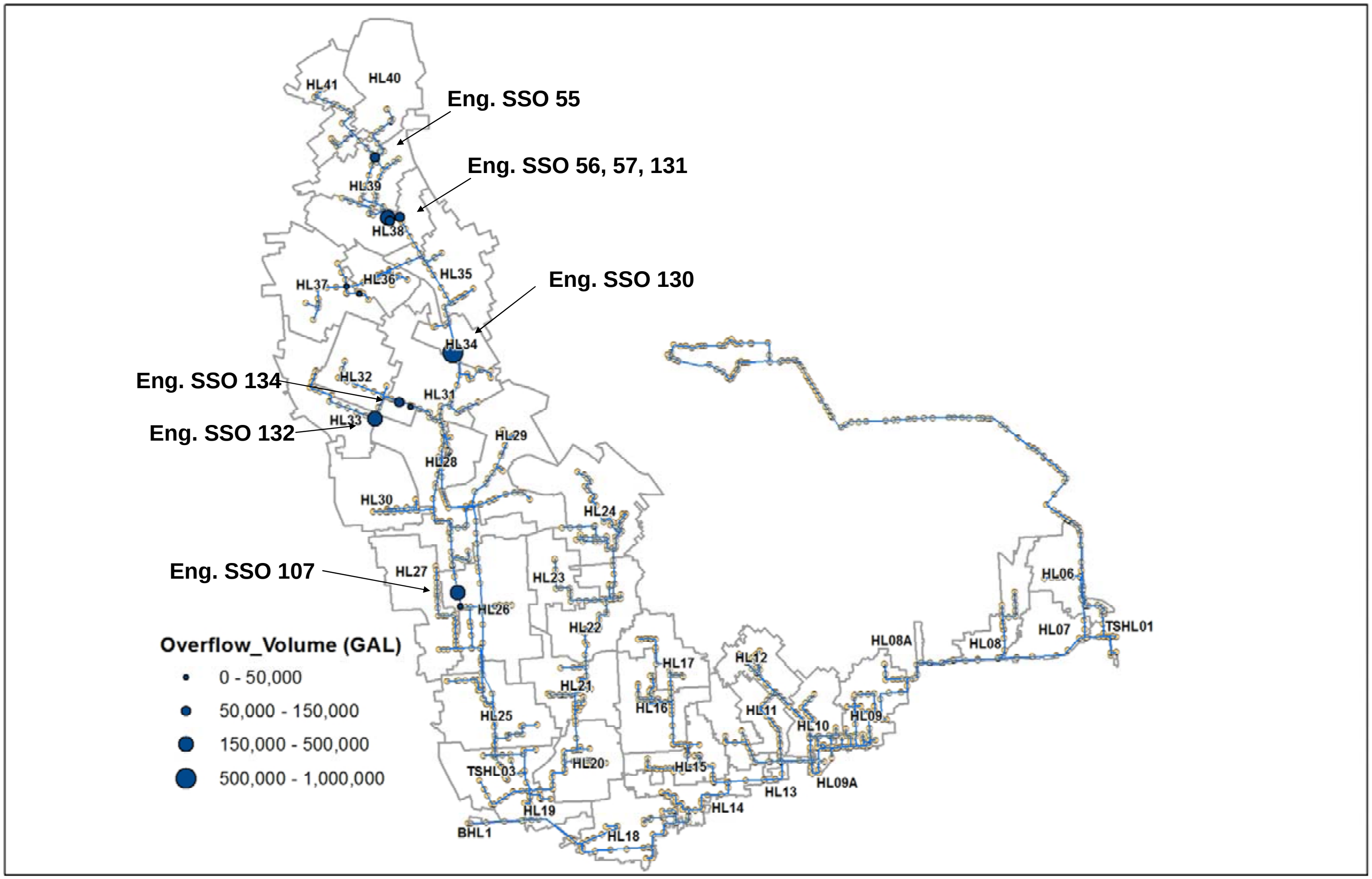


Figure 6-28. Simulated lost volumes from engineered SSOs for November 16 storm

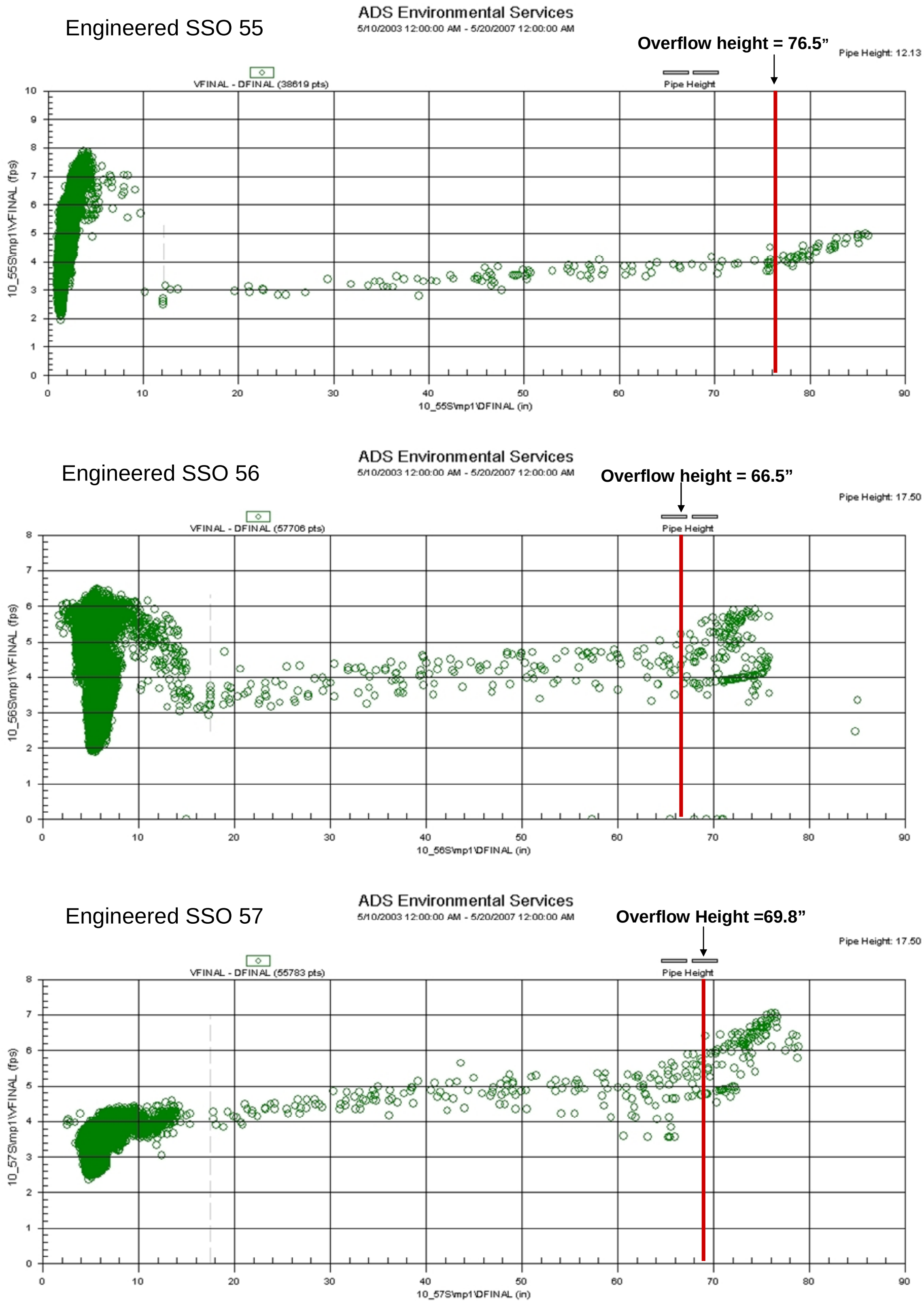


Figure 6-29. Evidence of overflow for engineered SSO 55, 56, and 57 between May 2003 and May 2007.

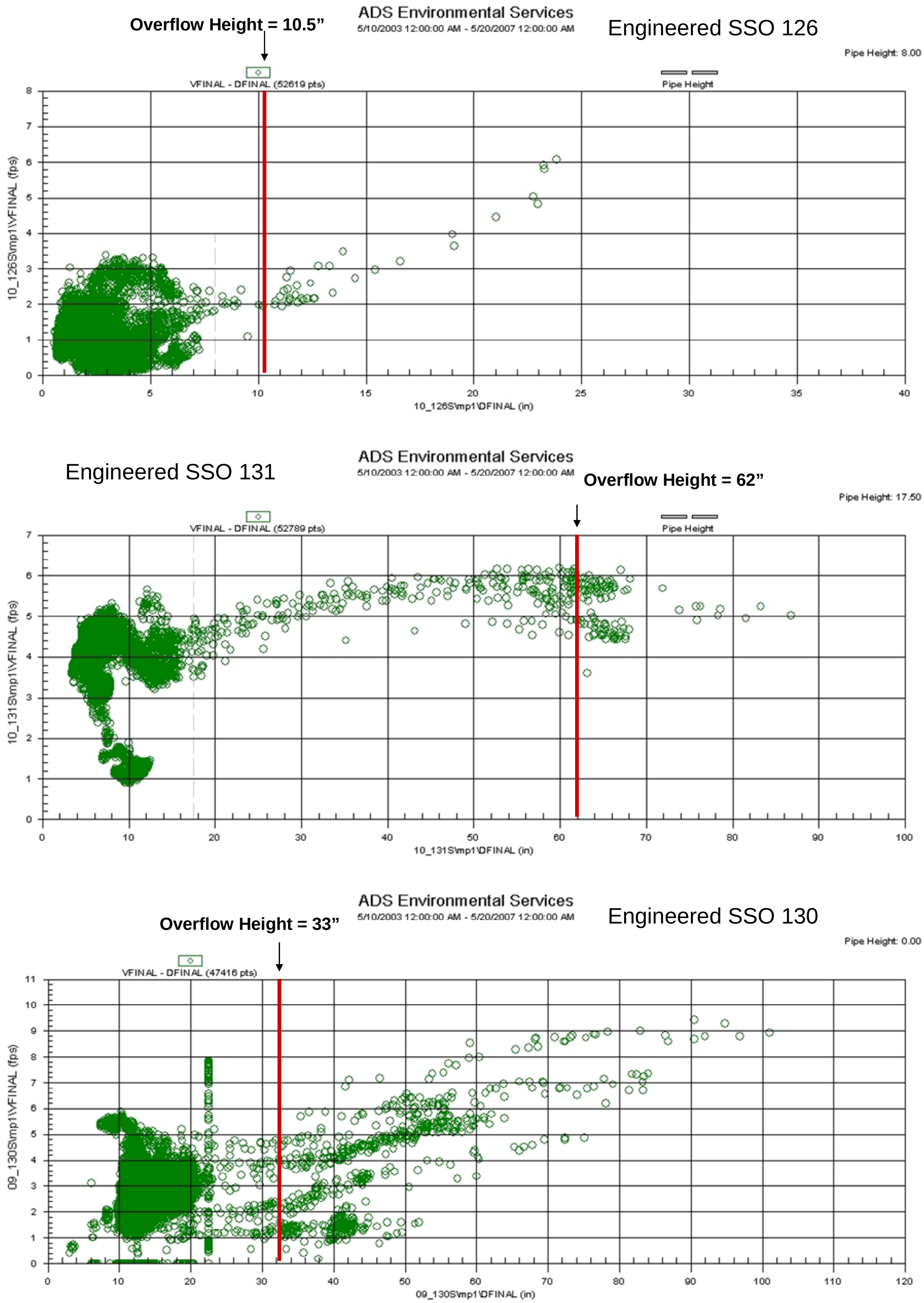


Figure 6-30. Evidence of overflow for engineered SSO 126, 131, and 130 between May 2003 and May 2007.

Model Validation with SSO Records:

Figure 6-31 shows the simulated SSO locations with historical capacity-related locations recorded between 2003 and 2007. Simulation results showed that there were several overflow manhole locations along the upper GRI. This includes that at 1200 Dukeland Street towards the upstream end of SC812. Capacity-related SSO locations were known along the GRI, however, there were frequently reported overflows near the HLI inverted siphon known as the BCDC SSO. The BCDC overflow was reproduced very well in the simulation. Table 6-6 shows the estimated SSO volumes during the July 5th and November 16th storms. The overflow volume was much larger for the lower part of the HLI than the estimates for other overflow locations in the upper GRI basins.

Table 6-6. Simulated SSO volume for July 5th and November 16th storm

Manhole ID	Location	July 5th (gal)	November 16th (gal)
S37CC_034MH	HL08A (HLI, BCDC)	1,776,300	6,123,000
S43EE_034MH	HL07 (HLI)	295,100	2,380,600
S43EE_049MH	TSHL01 (HLI)	756,800	1,796,300
S43EE_013MH	TSHL01 (HLI)	20,800	178,200
S13OO_007MH	HL28 (GRI))	8,500	55,200
S13EE1005MH	HL35 (GRI)	0	26,300
S09KK1010MH	HL39 (GRI)	0	16,300
S13SS_010MH	HL31 (Dukeland Street)	0	13,900
S07WW_010MH	HL32	0	10,500
S13QQ_002MH	HL28 (Dukeland Street)	3,900	8,300
S35AA_023MH	HL09 (HLI)	0	8,000
S09WW_014MH	HL32	0	7,900
S11WW_007MH	HL32	0	3,900
S13QQ_001MH	HL28 (Dukeland Street)	0	2,000
S11EE1005MH	HL35 (GRI)	0	1,100
S07AA1012MH	HL37	0	1,000
Total (gal)		2,861,400	10,632,500

The simulated SSO volume of over 6 million gallon at the BCDC manhole (S37CC_034MH) for the November 16th storm is tremendous. To validate the order of magnitude in SSO volume at BCDC, real SSO volume was calculated from newly installed flow meters, HLS1 and HLS2. HLS1 was installed at the upstream end of the HLI siphon while HLS2 was installed at the downstream end of the siphon (figure 6-32). Since HLS2 is directly upstream of the inflow manhole from Lower Jones Falls Interceptor, there is no incoming or outgoing flow between the two meters except water that is lost from the system through the SSO. Figure 6-33 shows the hydrographs of the two flow meters for the September 27th storm in 2008, which had approximately 3.6 inches of rainfall. The deviation of the two hydrographs shows there was a large SSO for more than 6 hours and the SSO volume is approximately 4 million gallons.

The November 16th storm in 2006 had 2.4 inches of rainfall which was 1 inch less than the September 28th storm. However, since it was considered with a higher RDII capture coefficient in winter, the simulated volume of 6 MG for the November 16th storm was considered reasonable.

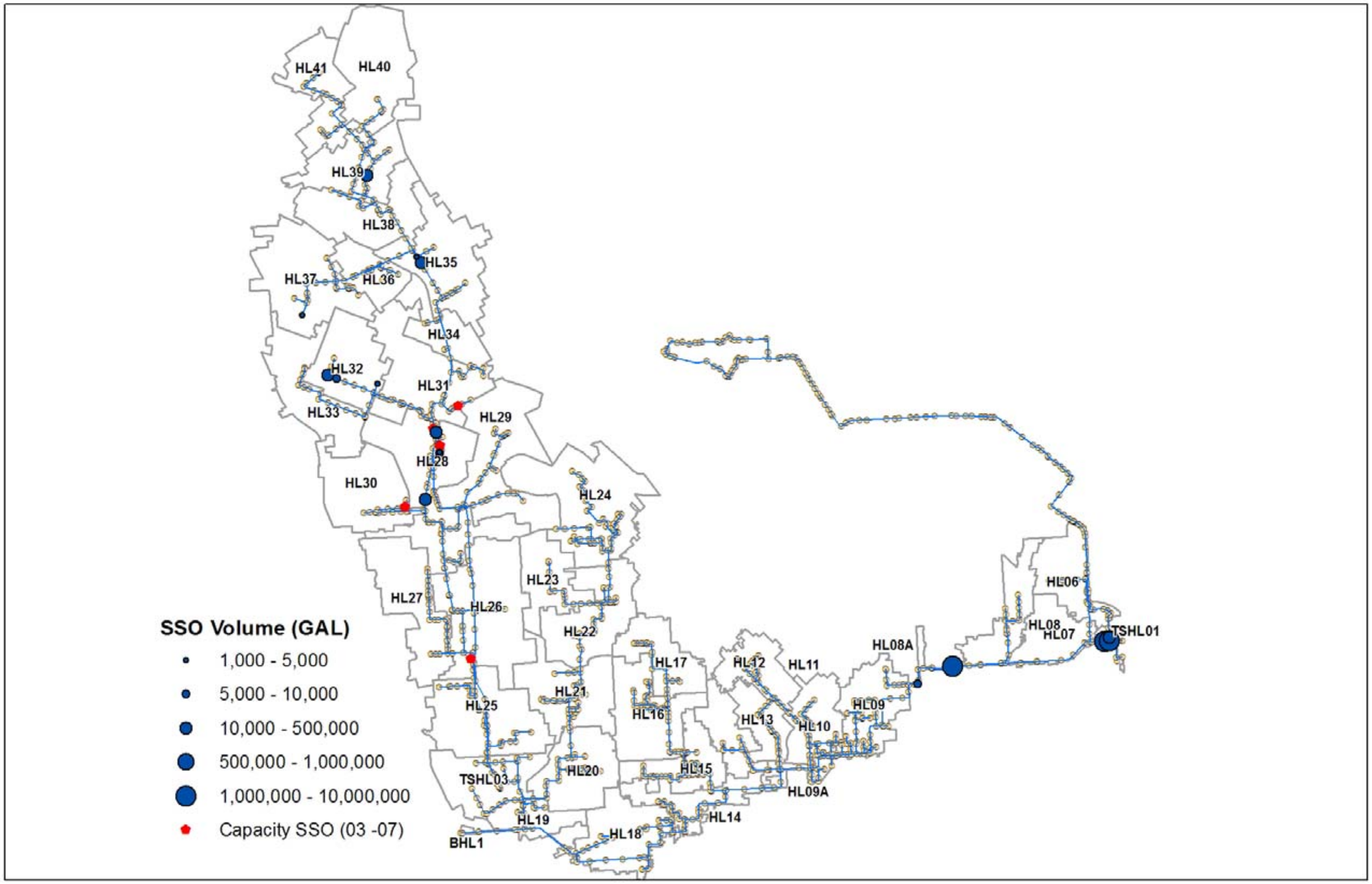


Figure 6-31. Simulated SSO locations for November 16th storm compared with recorded capacity-related SSO locations (2003 – 2007)

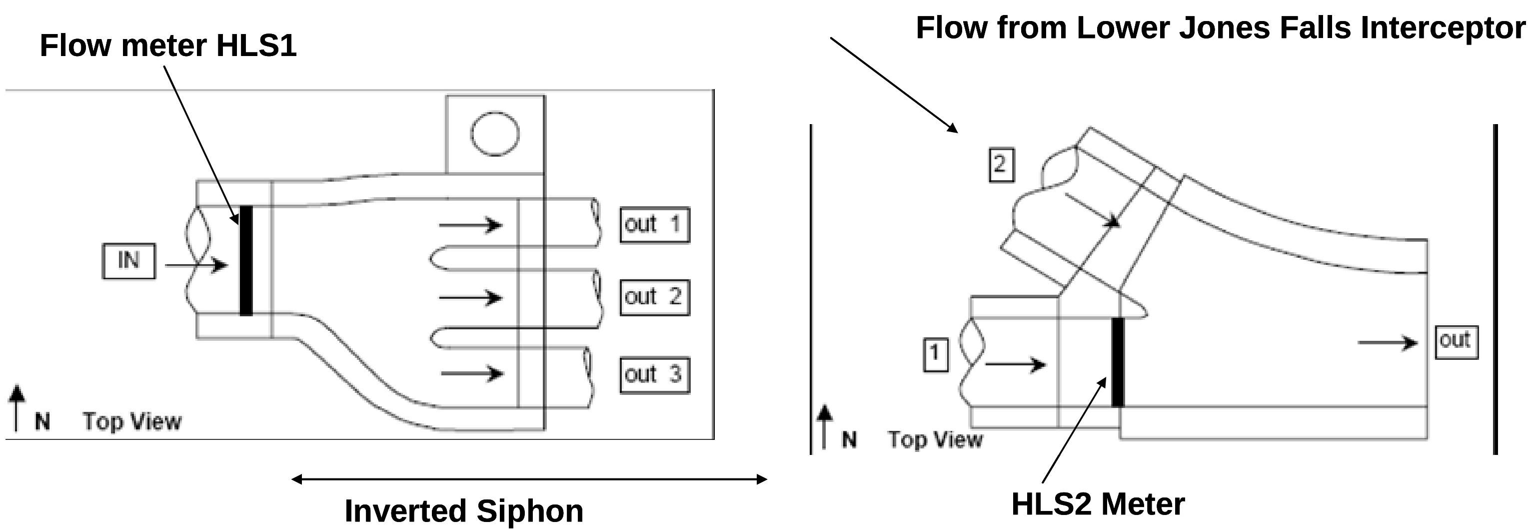


Figure 6-32. Flow Meter schematic of HLS1 and HLS2

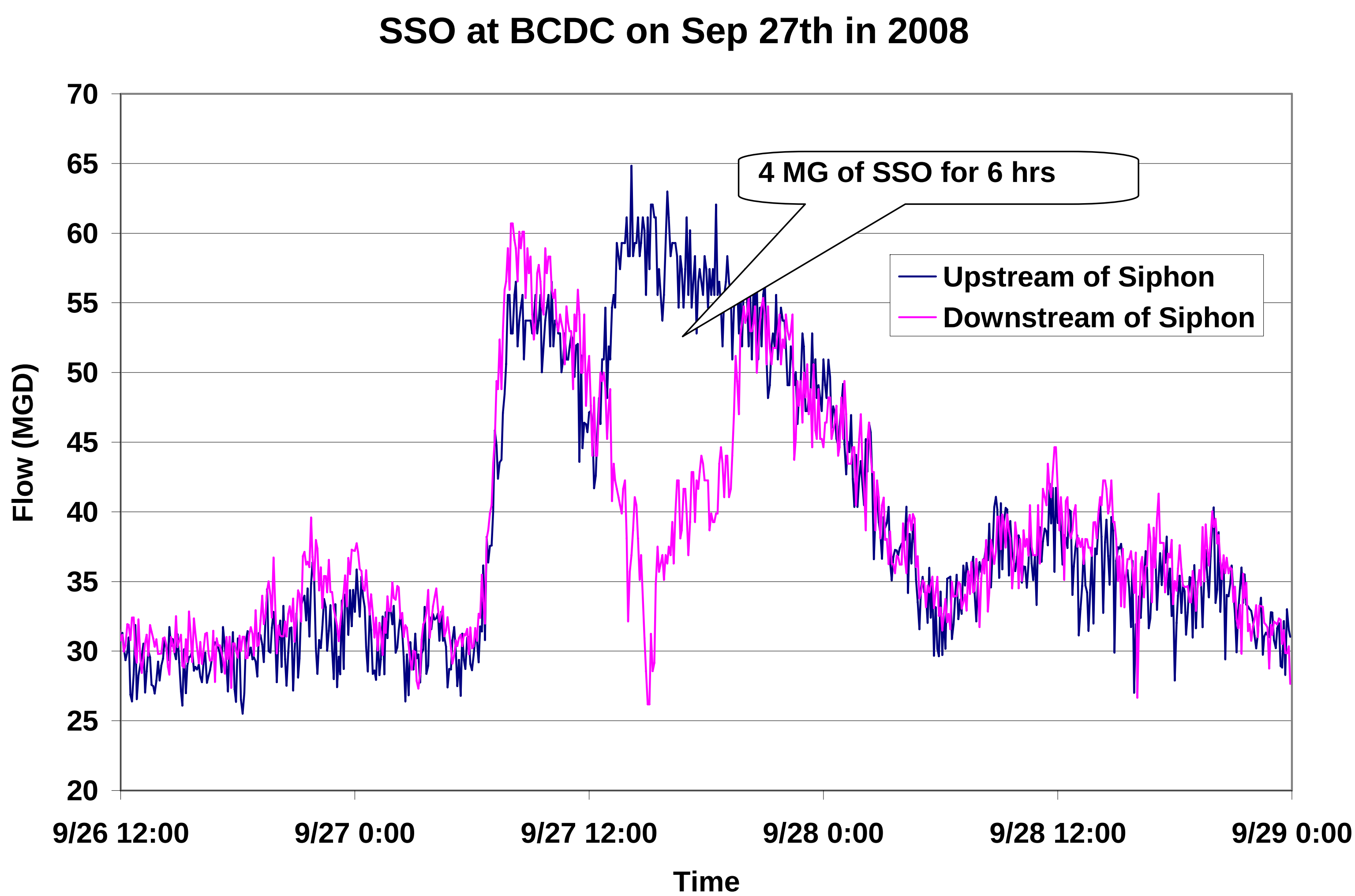


Figure 6-33. Hydrographs at HLS1 (upstream of the siphon) and HLS2 (downstream of the siphon) for September 28th storm in 2008

6.4 FUTURE REFINEMENTS

The model has been calibrated based on monitoring and field data available to the HLSS team as of December 2008, and the results were satisfactory system-wide, as well as for specific-meter data (where the data is considered acceptable). However, there are several potential refinements that have been identified to further improve model calibration, especially in places where critical field data can be available in the near future. This section describes several assumptions made in this study and the status of field inspection as of December 2008. Further use of the remaining field data is also discussed here.

6.4.1 Assumptions for fine-tuning Calibration

Pipe Size:

There were many sewer pipes for which the sizes could not be verified from any available data source. As-built drawings were the most reliable source of pipe sizes; however, the pipe size information was not available in all drawings. Direct measurement was very difficult given the sediment depth, high water levels and with many manholes exceeding 30 feet in depth.

Even for pipes with available field data, there were challenges associated with determining pipe sizes. There were four different data sources for pipe size: as-built drawings, existing GIS, manhole inspection reports (upstream and downstream manholes), and CCTV inspection databases. Table 6-7 shows the number of data sources available as of October 2008, and the number of data contradictions pertinent to pipe sizes among the various data sources. These contradictions are currently being reviewed by the field data QA/QC team and, once finalized, will be used to update the model network database.

Table 6-7. Number of contradiction in pipe size from different data

Available Data	Total	No contradiction	With contradiction
4	359	229	130
3	333	196	137
2	202	129	73
1	133	N/A	N/A
Total	1027	554	340

The HLSS team assumed pipe sizes based on neighboring pipes and flagged them “AS – assumed” for these pipes where data are neither available nor verifiable.

Pipe Invert Elevations:

Pipe invert elevations were determined by subtracting depth-to-invert found during manhole inspections from the manhole rim elevation measured by land surveys. For the HLI and any other pipe segment where manhole depth-to-invert data was not available or reliable, as-built information was utilized for determining pipe inverts.

Pipe invert elevation was assumed only if none of these data sources were available, or if the pipe slope determined by the field data indicated that flow was going uphill; there were approximately 20 sewer pipes out of approximately 1000 model sewer pipes where field data showed a sewer pipe having an upward slope. In these cases, sewer pipe invert elevations were assumed by the HLSS team with reasonable slope values.

Sediment Depth:

Sediment depth data was available for pipes where sonar inspections were conducted or flow metering site sheets were available. There were a few locations where the sediment depths were assumed to reproduce high surcharges along lower the GRI and the inverted siphon directly downstream of HL16. Preliminary CCTV and SONAR data indicate that the lower GRI is difficult to inspect due to the pipe size in conjunction with the variability in sediment depths and water depths. The SONAR device attached to the CCTV camera will alternate between being submerged and hovering above the water level on a single sewer pipe inspection. Any assumed sediment depths will be replaced with measured depths where data becomes available.

6.4.2 Status of Field Inspection

Several types of field data were reviewed and used for the hydraulic model development. This section summarizes the status of field data collection.

Land Surveys:

Land survey data have been used to provide rim elevations of the model manholes. As of December 2008, 952 manholes have been surveyed among the 1,061 manholes in the model extent. The rest of manholes have not been surveyed due to several field conditions, including paved-over manholes or prohibited-access. Any data that becomes available until December 2008 has been be imported into the model network. All questionable data found during the network profile check was transferred to the HLSS field data QA/QC team for further verification and approval. Figure 6-34 shows all surveyed manholes in the model network as of December 2008.

Manhole Inspections:

Manhole inspection data provided invert depths and pipe sizes of all incoming and outgoing pipes for each manhole. Invert depth was subtracted from land surveyed manhole rim elevation to derive the invert elevation. Pipe sizes from manhole inspections were used to confirm or update the sizes of modeled pipes. As of November 2008, 824 manholes were both surveyed and inspected among 1,061 included in the model (Figure 6-34).

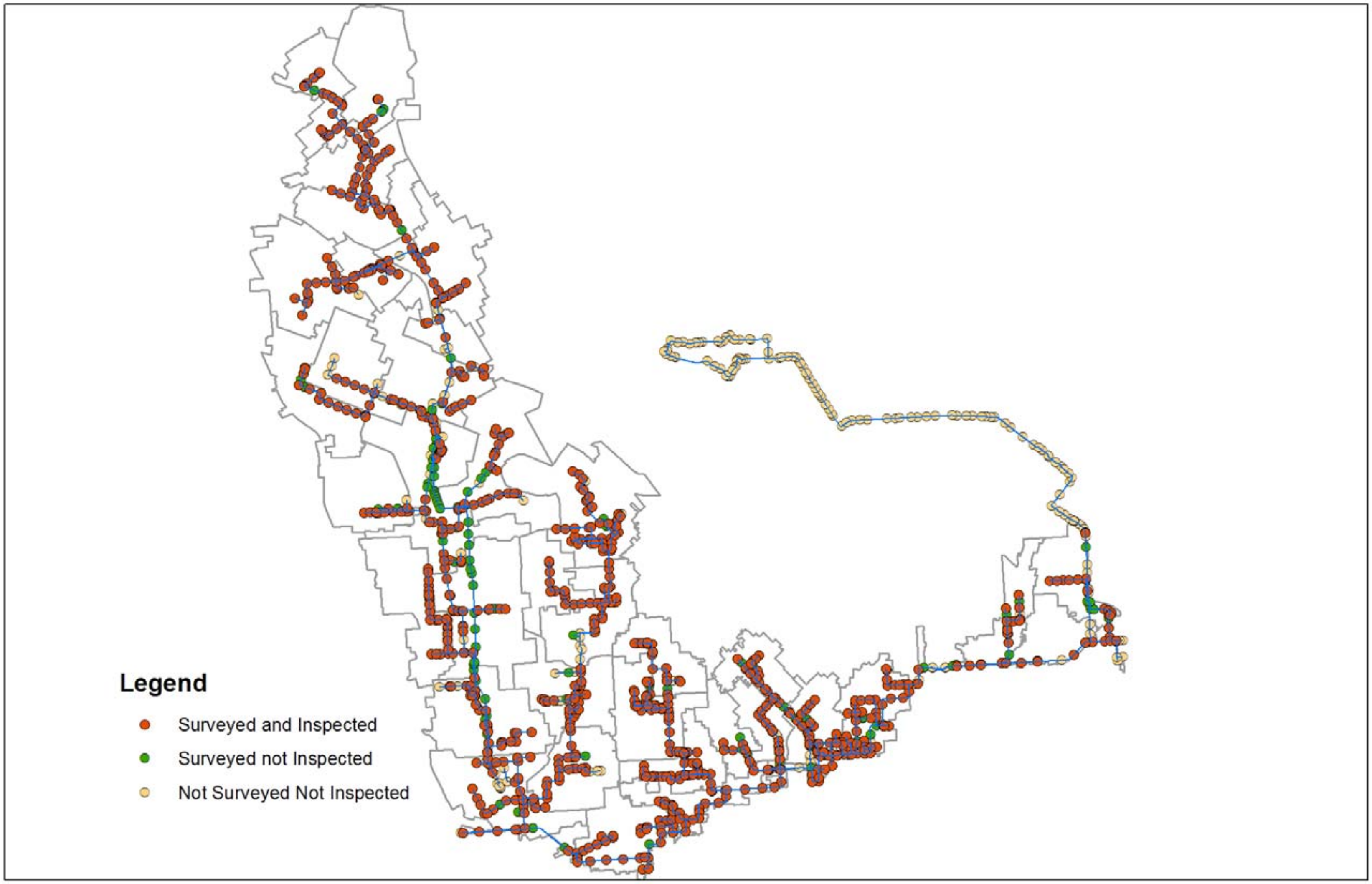


Figure 6-34. Status of land survey and manhole inspection for model manholes

CCTV Inspections:

The CCTV inspection data has not been directly used for model development except for confirming pipe sizes, and the data are still being collected and undergoing 1028's QA/QC process.

Sonar Inspections:

Sonar inspections have been conducted for 18,000 linear feet of the HLI from 23II_016MH to S45EE_055MH. This covers approximately 75% of the HLI and the debris information has significantly enhanced the accuracy of the model along the HLI. The lower part of the GRI is expected to be inspected by CCTV and sonar technology in the near future. It is expected that the GRI sediment data can further enhance the model calibration especially for surcharge depth.

Smoke Testing:

Smoke testing in the HLSS drainage area began in August 2008. As of December 2008, 190,000 linear feet of pipes have been smoke-tested and an additional 90,000 ft will be smoke tested in Spring 2009. Smoke-testing flow basins were selected by the team based on RDII severity (or capture coefficient) and historical SSO records. For the model calibration presented in this report, smoke testing results have not been incorporated. These results will be reviewed once it undergoes the necessary QA/QC to identify any significant and specific RDII sources.

Table 6-8. Smoke tested basins as of December 2008

Sub-sewershed	No. of Pipes	LF of Pipes	Tested month
HL31*	124	23,552	Aug-08
HL32	81	20,457	Aug-08
HL33	94	20,404	Aug-08
HL34	86	15,491	Sep-08
HL35	201	36,021	Sep-08
HL36	62	11,504	Sep-08
HL30	194	30,247	Oct-08
HL27	248	34,469	Oct-08
HL40	117	20,482	Nov-08
Total	1207	212,627	

* west side of light rail only

6.4.3 Final Calibration and Validation

There are several places where model calibration can be enhanced so that the HLSS team can accurately evaluate the potential for future SSOs and the effectiveness of specific rehabilitation alternatives. These key locations are listed below along with the planned methodology to enhance the model calibration.

Engineered SSOs near Liberty Heights Avenue

There are three active engineered SSO locations in HL33 and HL32 near Liberty Heights Avenue, and two of these have exhibited frequent overflows. The City needs to eliminate these engineered SSOs without causing future SSOs per CD requirements. Therefore, the model should be further refined at the local level and extensively use smoke testing data (that will be available in the near future) and existing CCTV data.

Lower GRI

The Lower GRI will be inspected by CCTV and sonar technology in the near future. The CCTV inspection has not yet been conducted due to high flow conditions even during dry weather and some debris along the GRI. Once the CCTV/sonar inspection data is available, the surcharge depths can be represented accurately and verified using the available monitoring data. Model enhancements along the lower GRI are important to evaluate the potential for SSOs at the confluence point of SC-812 and the existing GRI.

High Level *Inverted* Siphon

Although surcharge depth and peak flow are well calibrated along the HLI, there is a need for further study on the High Level Inverted siphon due to frequent overflow occurrence reported at both ends of the siphon. Metered data at both ends of the siphon are currently being collected by the City, and will be further reviewed to determine if the siphon plays an important role in the HLI capacity limitations.

In addition to these key locations, CCTV data and smoke testing data will be reviewed and analyzed on a system-wide basis. For inflow type defects found in CCTV, they can be incorporated into the model as additional I/I sources on a per-linear-foot basis. Rooftop connections found by smoke testing can be incorporated in the model as a 100% RDII source. Structural pipe defects found through CCTV inspection, such as major joint offsets and pipe collapse, will be counted on an inter-basin basis to determine whether or not there are any correlations between the RDII severity and the found defects. Once they are appropriately represented in the model, the effect of pipe rehabilitation or rooftop disconnections can be evaluated as alternatives.

A good example of field data, which was effectively used to enhance model accuracy, is sediment profile along the HLI. The calibrated model with sediment profile will be used for alternative analysis such as heavy cleaning of the HLI. Thereby, these further model refinement with field data will help evaluate the effectiveness of alternatives so that the City the can choose the most cost-effective solutions.

The finalized calibrated model network will be synchronized with GIS. Since GIS will take several types of data from the hydraulic model such as pipe invert elevation, the data in the model will be organized thoroughly using Flags in consultation with the HLSS GIS specialists.

THIS PAGE INTENTIONALLY LEFT BLANK

SECTION 7 – USE OF THE CALIBRATED HLSS MODEL

A series of reports will be submitted at the completion of major tasks during the course of this project. Prior to initiation of these reports, a modeling work plan that briefly reviewed the steps involved in model development and calibration was submitted to the City. This report describes the calibration and validation work performed by the HLSS team. As discussed earlier, the HLSS team initially calibrated the model for summer and winter periods to accurately reproduce the corresponding RDII and delayed infiltration volumes. Subsequent to the guidance from 1015, this calibrated model has been refined with annual average capture coefficients in order to maintain consistency with other sewershed studies. This section first describes the median R refinement for model calibration and subsequently the application for baseline/future conditions and alternatives analysis.

7.1 MEDIAN R WET-WEATHER CALIBRATION

Following completion of the dry weather calibration discussed in Section 6.2.3, the HL team initiated wet weather calibration was initiated for the High Level Sewer System. As stated in Section 4.3.3 of the model development report, the capture coefficients were developed from Sliicer.com and entered into the model's sub-catchments as "Fixed Runoff Coefficients". The initial InfoWorks model runs were based on default values for basin slope and basin width and initial values of 0.015 for runoff routing values (Manning's surface roughness factor). The sub-catchments were divided into two runoff surfaces to capture both inflow driven I/I and infiltration driven I/I. The primary runoff surface (referred to as Runoff1 in figure 1) captured the inflow driven I/I and the secondary runoff (Runoff2 in figure 2) area captured the infiltration driven I/I. During the winter, both inflow and infiltration are present due to relatively higher ground water level; during the summer, only inflow is present with very little infiltration. Only the primary runoff surface for inflow driven I/I was used to calculate summer I/I, while both the primary and secondary runoff surfaces were used to calculate the winter I/I.

The HLSS initial model calibration used the two different models for summer and winter. However, the technical management team guided the HLSS Team to combine the summer and winter models into an all-year model using Median R capture coefficient. The objective was to maintain consistency among various sewershed studies and to ensure that the City-wide macro model is compiled from individual sewershed models that use the same basis. To fulfill the request, the HLSS Team calculated median values of summer and winter for both depression storage and capture coefficient and used these for the Median R model development. In the Median R model, as illustrated in Figure 1, the inflow driven I/I from the primary runoff surface stays the same, while the infiltration driven I/I from the secondary runoff surface was halved from the winter model.

After the team's review of the results for all the 24 storm events using the Median R model, some parameters were adjusted to more accurately predict the I/I responses exhibited in the flow metering data. Adjustments were made based on sensitivity analyses conducted using the Median "R" model. In order to match the flow volume at some places, the slope and runoff routing values were adjusted. Similarly, the basin width was adjusted to match the recovery duration and peak timing.

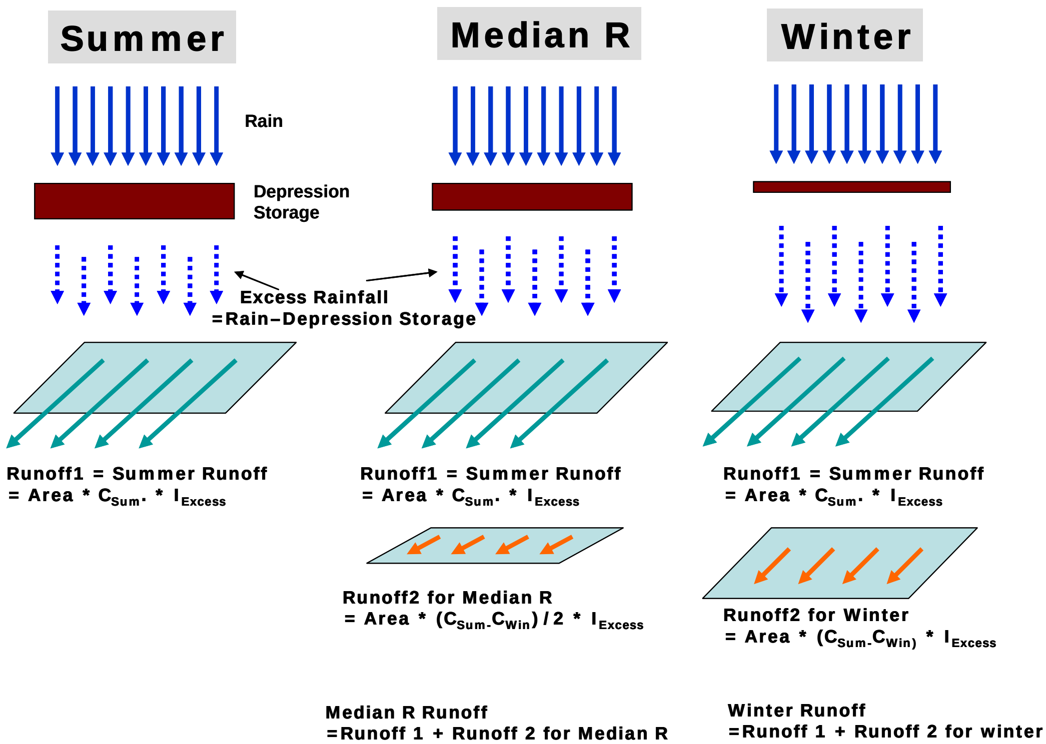


Figure 7-1. Model development process using the Median R capture coefficient

Based on guidelines provided in the City Technical Management Team, the following methods were adopted for evaluating the wet weather model calibration/validation of results and determining the adequacy of calibration for application to future baseline and alternatives analyses:

- Modeled peak flow rate should be within -10% and +25% of the observed peak rate;
- Modeled volume of flow should be within +20% and -10 % of the observed;
- Modeled depth of flow in surcharged sewers should be within +18 inches and -4 inches in sewers 21 inches in diameter and larger (and within +6 inches and -4 inches in sewers smaller than 21 inches in diameter) of the observed;

- Modeled depth of flow at non-surcharged critical points in the system, i.e., at SSO structures, should be within 4 inches of the observed; and
- Shape and timing of the hydrographs should be similar.

7.1.1 Comparison of Metered and Modeled Results

Based on a comparison of metered and modeled results, shown in Appendix 1 and Attachment 2, it appears that the observed and modeled values are dissimilar at many sites. This is due to the differences in I/I characteristics in summer and winter seasons. Summer storms typically are of shorter duration and higher intensity than the winter storms. In addition, the soil is dryer and the water table is lower than in winter. This leads to lesser runoff per unit rain volume in summer. The winter storms are typically longer in duration, but lower in intensity than the summer events. With wetter ground and a higher water table, more runoff occurs per unit rain volume during winter storms. Figure 2 below shows this typical behavior which is evident at all the sites in the High Level Sewershed:

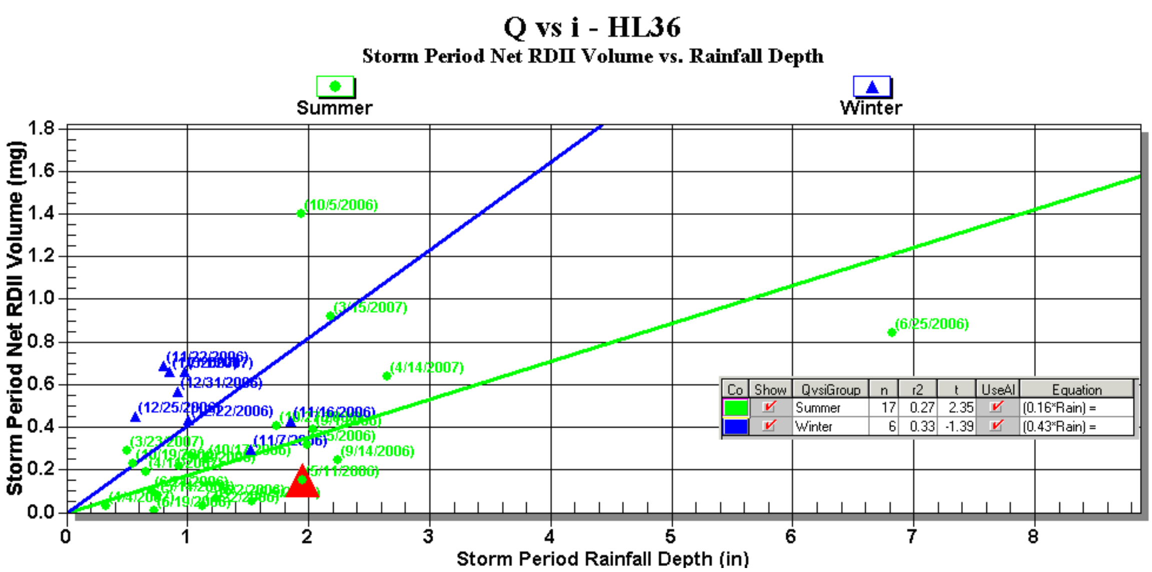


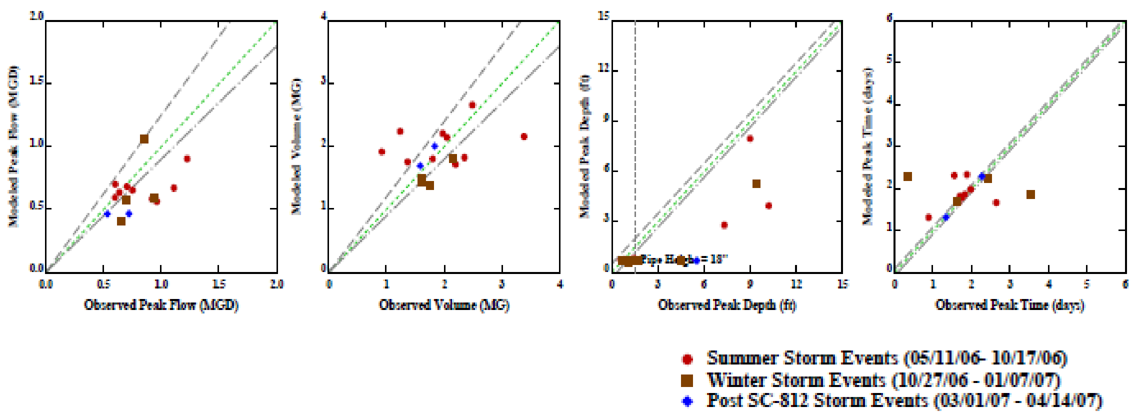
Figure 7-2. Rainfall Depth Versus Net RDII Volume

The winter storms are shown in blue triangles and the summer storms in green circles. The graph shows that more than twice the amount of rain enters the sewers during winter than in summer. This led to difficulties in calibrating the model to accurately predict both types of storm events. If the model was calibrated to only summer events, potential deficiencies in the system might not be fully captured; however, if only calibrated to the winter storms, the required improvements might be grossly over-predicted. A median “R” was used in the model as a compromise, consistent with the guidelines provided by the City Technical Management Team. By using this method, the model over-predicts summer storms, but under predicts winter storms. However, the calibration guidelines are generally met.

7.1.2 QA/QC

In order to assess the model performance to predict system responses, the team developed time series and goodness of fit comparisons for the observed vs. predicted data. See Appendix 1 for a time series comparisons of observed versus predicted at each metering location and Appendix 2 for the statistical comparison of observed and modeled values. Appendix 3 displays the goodness of fit comparisons of the observed and predicted volumes, depth and peak flow rates. The calibration criteria for peak flow rate, volume, and surcharge depth are shown as dotted lines (on either side of the 45-degree line that represents a strong correlation between the two). As seen in the example plot below, some of the summer storms are over-predicted, but very few of the winter storms are under-predicted.

In addition, the team generated and reviewed observed vs. predicted graphs and goodness of fit plots generated using InfoWorks output data, to assess the shape and timing of the hydrographs.



The design storms to be used in the capacity analysis are more typical of summer type storms than of winter type storms. Calibrating the model using the median “R” guidance from the technical program management team is believed to yield a conservative capacity estimate.

Two other major reports to be submitted by the HLSS team subsequent to submission and review of this model calibration report include:

- Baseline Analysis and Capacity Assessment Report.
- Alternatives Analysis and Recommendations Report.

The scope of these two future reports is briefly discussed in this section.

7.2 BASELINE ANALYSIS AND CAPACITY ASSESSMENT REPORT:

When the dynamic hydraulic model of HLSS is suitably calibrated and validated, it will be used to characterize the collection system performance under baseline conditions for a variety of design storms. The HLSS has linkages with other sewersheds which are defined using flow metering data at various boundary locations in the calibrated model. However, for future baseline conditions, 1015 will review the historical flow monitoring data and develop boundary conditions for the design storms. According to the CD, the City will need to determine peak flows for each of its sewersheds with future flow projections for the design storms. The flow projections have been provided by 1015 to the HLSS team.

The HLSS team will incorporate appropriate boundary conditions and future flow projections in the calibrated model to predict local and system-wide hydraulic conditions in the sewershed. The result of these analyses will be summarized in the Baseline Analysis and Capacity Assessment report and submitted to the City. System responses will be reported for the following storm events:

1) A 3-month design storm having a duration equal to the time of concentration for the sewershed;
2) A 20-year, 24-hour design storm; and
3) Five intermediate storm events, one of which will be a 10-year, 24-hour duration design storm.

The four other intermediate storms will be 1-year, 2-year, 5-year and 15-year, 24-hour duration design events. Since the Washwater Lake at Ashburton WFP has undergone recent rehabilitation (WC1143), a meeting will be scheduled with the rehabilitation project contractor to discuss flow conditions from both the Washwater Lake and sedimentation basin (in terms of the discharge rate and frequency). The baseline assessment report will include the following information:

- DWF capacity of the pipes in the model;
- Results of the return period analysis (RPA) from InfoWorks - this would summarize the storm frequency required to surcharge or flood a pipe;
- Flow restrictions that occur during wet weather events;
- Maximum allowable flow before an overflow occurs;
- Table with SSO volumes and their corresponding locations; and
- Areas with high inflow and infiltration correlated to the results from field inspections.

The above information will be presented in the form of summaries about hydraulic conditions and associated figures and tables in the baseline report.

7.3 ALTERNATIVE ANALYSIS AND RECOMMENDATIONS REPORT

In the future conditions analysis, the model will accommodate some modifications to represent conditions prevailing in 2020. The future conditions model will account for both population increases and the effects of pipe deterioration projected for 2020. Similar to the baseline analysis, all seven design storm events will be used to assess the local and system-wide hydraulic conditions. The future conditions model will include any proposed improvements to the collection system that are not included in the baseline model but are scheduled for completion prior to 2020. The alternatives analysis will involve a set of criteria to evaluate the level of SSO control. These criteria are grouped into three main categories:

- Economic Impact
- Implementation Impact
- Operational Impact.

A quantitative decision process will be developed using these three categories in which weighting factors will be assigned to rank the alternatives. The alternative analysis report will include the following information:

- All maps and tables from the baseline analysis report;
- Alternatives ranking with justification (improvements, cost analysis, constructability assessment and implementation assessment);
- A summary of the recommended plan including maps and expected costs; and
- A map of locations where HGL comes within 10 feet of the ground surface (SSOs will be eliminated, but there may be cases where the HGL is not the cause of flooding but has a potential to enter the basements of homes. These predicted locations will be identified.

Upon completion of the modeling task for the HLSS project, the team will submit a CD or DVD to the City and 1015 containing the final version of the sewershed model. The InfoWorks model will include the following model configurations:

- Calibration conditions.
- Existing conditions (if different from calibration conditions)
- Future flow configurations
- Baseline conditions
- Any alternatives presented in the submitted reports.
- The final recommended plan.